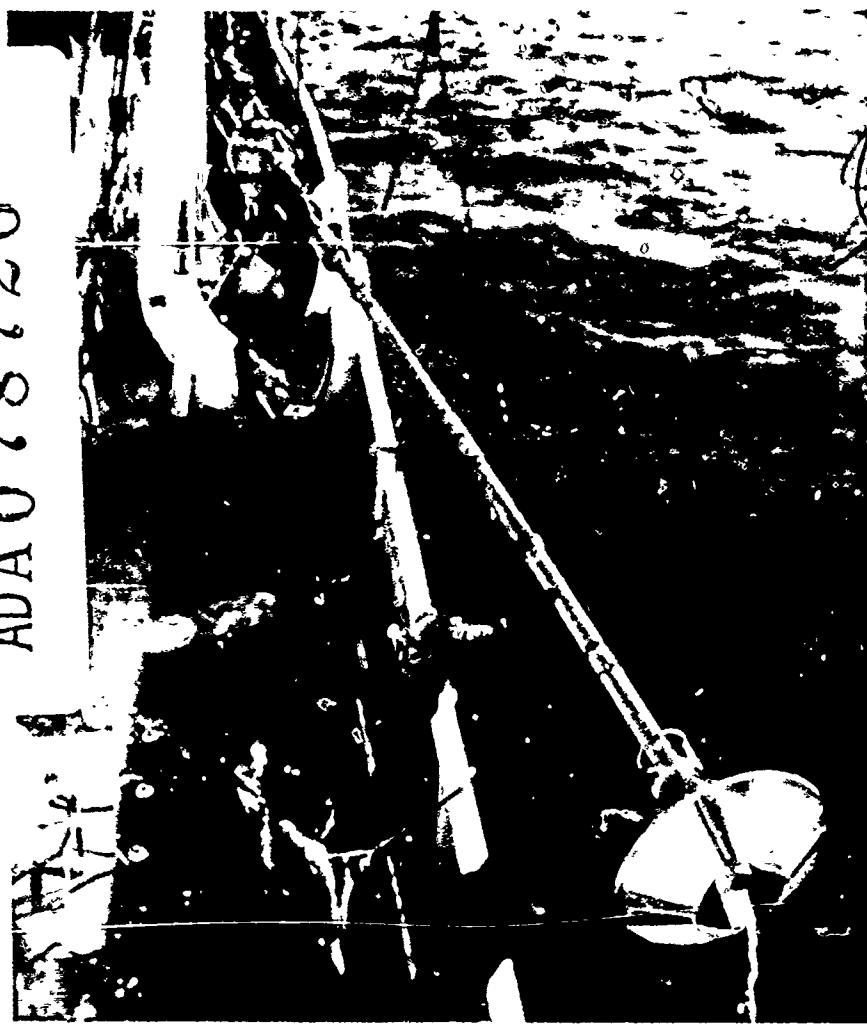


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Naval Construction Battalion Center, Port Hueneme, California 93043

SEAFLOOR SOIL SAMPLING AND GEOTECHNICAL PARAMETER DETERMINATION—HANDBOOK

by

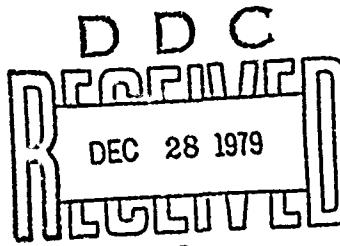
H. J. Lee and J. E. Clausner

August 1979

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obtain measurements of these properties to several different levels of accuracy. A flow diagram identifies the major decision blocks for selecting an appropriate properties determination program. The programs recommended vary from estimation and approximate measurement to coring, detailed laboratory testing, and disturbance correction, depending on the tolerable level of error. The greatest accuracy achievable is a possible error range of $\pm 20\%$ in shear strength. All aspects of the process of obtaining parameters are described: corers, coring procedures, coring accessories, oceanographic support vessels, core handling, laboratory testing, and test result analysis. Procedures are also given for correcting for coring disturbance in measurement of laboratory shear strengths to estimate the correct in-place strengths.

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1. Geotechnical properties 2. Seafloor construction I. YF52.556.091.01.101A

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CONTENTS

	Page
1. INTRODUCTION	1
1.1 PURPOSE	1
1.2 BACKGROUND	1
1.3 BRIEF GUIDE TO USE OF THIS HANDBOOK	1
2. NONPHYSICAL SAMPLING	9
2.1 DESK-TOP TECHNIQUES	9
2.1.1 Near-Shore Areas	9
2.1.2 Deep Ocean Areas	10
2.1.3 Terrigenous Sediments	10
2.1.4 Sediment Property Selection	15
2.2 QUALITATIVE ACOUSTIC PROFILING	21
2.3 QUANTITATIVE ACOUSTIC PROFILING	22
2.4 PENETROMETERS	22
3. PHYSICAL SAMPLING	27
3.1 BOX CORERS	27
3.1.1 Description	27
3.1.2 Procedures	30
3.2 FREE-FALL CORERS	32
3.2.1 Description	32
3.2.2 Procedures	35
3.3 SHORT CORERS	35
3.3.1 Description	35
3.3.2 Procedures	39
3.4 LONG-PISTON CORERS	40
3.4.1 Description	40
3.4.2 Procedures	47

CONTENTS (continued)

	Page
3.5 ASSOCIATED CORING EQUIPMENT	52
3.5.1 Wire Rope	52
3.5.2 Terminations	54
3.5.3 Winches	54
3.5.4 Liners	55
3.5.5 Pingers	55
3.5.6 Releases	56
3.5.7 Core Catchers	57
3.5.8 Sources of Equipment	57
4. SURVEY PLATFORMS	61
4.1 NAVOCEANO SHIPS	62
4.2 NAVAL RESEARCH LABORATORY SHIPS	62
4.3 NOAA SHIPS	62
4.4 U.S. GEOLOGICAL SURVEY (USGS) SHIPS	63
4.5 UNOLS SHIPS	63
4.6 COMMERCIAL OCEANOGRAPHIC RESEARCH VESSELS	63
5. CORE HANDLING	67
5.1 SECTIONING	67
5.1.1 Piston or Gravity Corers	67
5.1.2 Box Corers	68
5.2 CORE STORAGE	68
5.3 TRANSIT	69
6. LABORATORY TESTING	71
6.1 RECOMMENDED TESTING PROGRAM	71
6.1.1 Required Engineering Properties	71
6.1.2 Special Engineering Properties	73
6.1.3 Required Mass Physical Properties	73
6.1.4 Index Properties	75

CONTENTS (continued)

	Page
6.2 TEST PROCEDURES	76
6.2.1 Undrained Shear Strength	76
6.2.2 Drained Strength Parameters	82
6.2.3 Consolidation (Settlement) Parameters	90
6.2.4 Water Content	91
6.2.5 Grain Density	93
6.2.6 Index Properties	93
7. DISTURBANCE CORRECTION	97
7.1 STRENGTH CORRECTION THROUGH RESIDUAL PORE WATER PRESSURE MEASUREMENT	97
7.2 TRIAXIAL TEST STRENGTH PROFILE FABRICATION	99
8. ACKNOWLEDGMENT	105
9. REFERENCES	107
APPENDIXES	
A - Background Research	113
B - Organizations Cited in Text	117
LIST OF SYMBOLS	121

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1. INTRODUCTION

1.1 PURPOSE

This handbook is written for ocean facility engineers who must design select, or predict the performance of anchor or foundation elements that fix structures to the seafloor. The engineer will, in most cases, be using existing procedures for foundation and anchor design and analysis. All these procedures require information on the physical properties of the seafloor sediments for implementation. This handbook provides guidelines for obtaining this information to a level of accuracy compatible with the importance and cost of the proposed seafloor facility. The handbook does not cover coral and rock sampling or their geotechnical properties. It also does not consider properties for deep foundations (subbottom depth >20 meters).

To obtain different viewpoints and also to cover items not considered in this handbook, the reader is referred to Noorany and Gizienski (1970), Ling (1972), and Richards et al. (1976).

1.2 BACKGROUND

Information presented in this handbook is based primarily on research conducted by the Civil Engineering Laboratory (CEL) over the past 8 years. During that time 10 sea cruises to nearby and distant locations were made, and large numbers of laboratory analyses on sediment core samples were obtained. Appendix A presents further background on the research philosophy and specific seafloor sediment sampling cruises.

1.3 BRIEF GUIDE TO USE OF THIS HANDBOOK

Though the subject of this handbook is very broad, the designer of ocean facilities usually needs a particular piece (or pieces) of information on cohesive seafloor sediment properties in order to complete the design.

Figure 1-1, which illustrates the decision steps and paths to be taken to reach the required knowledge of cohesive seafloor sediment properties, can be used as a decision chart by the user. Decision steps taken are based on the knowledge given in Tables 1-1 and 1-2 and Sections 2 through 7 of this handbook. These handbook sections are briefly abstracted as follows:

Table 1-1. Design Guidelines for Seafloor Operations

Subject	Publication ^a	Comments
Foundations	<p>Naval Facilities Engineering Command, Design Manual DM-7, Soil mechanics foundations and earth structures, Mar 1971</p> <p>Naval Civil Engineering Laboratory, Technical Report R-799, Interim design guidelines for seafloor footing, by H. G. Herrmann and P. J. Valent, Oct 1973</p> <p>Naval Civil Engineering Laboratory, Technical Note N-1246, Foundations for small seafloor installation, by H. G. Herrmann, Sep 1972</p> <p>North American Rockwell Corporation, Handbook of ocean and underwater engineering, Chapter 8, 1969</p>	<p>A general soils design handbook intended primarily for use on land; many procedures applicable to underwater use</p> <p>Most detailed guide book for seafloor footing design</p> <p>A simplified version of TR-799</p> <p>A handbook for larger (particularly pile-supported) structures</p>
Anchoring	<p>Naval Facilities Engineering Command, Design Manual DM-26, Harbor and coastal facilities, Jul 1968</p> <p>Civil Engineering Laboratory, Handbook for uplift-resisting anchors, by R. J. Taylor, D. Jones, and R. M. Beard, Sep 1975</p> <p>Civil Engineering Laboratory, Long-term holding capacity of statically loaded anchors in cohesive soils, by R. M. Beard (1979)</p>	<p>A handbook for drag anchors and associated mooring equipment, some design information</p> <p>Complete summary of uplift-resisting anchors and design information (holding capacity information is out of date)</p> <p>Revised holding-capacity prediction procedures</p>
Breakout	Naval Civil Engineering Laboratory, Technical Report R-755, Unaided breakout of partially embedded objects from cohesive seafloor soils, by H. J. Lee, Feb 1972	Method for predicting force needed to dislodge an embedded object

^aComplete entries will be found in Section 8, REFERENCES.

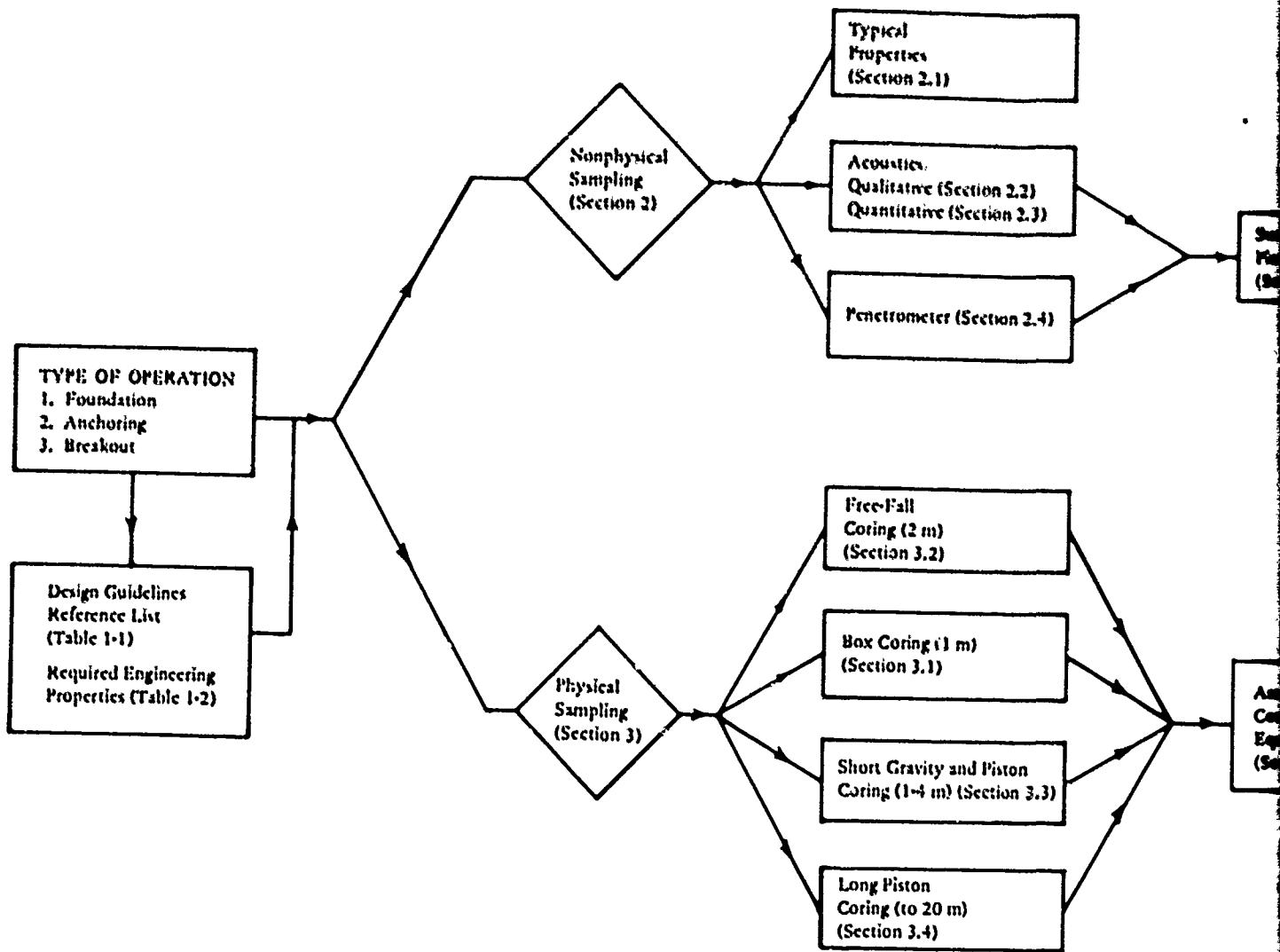


Figure 1-1. Flow and decision chart.

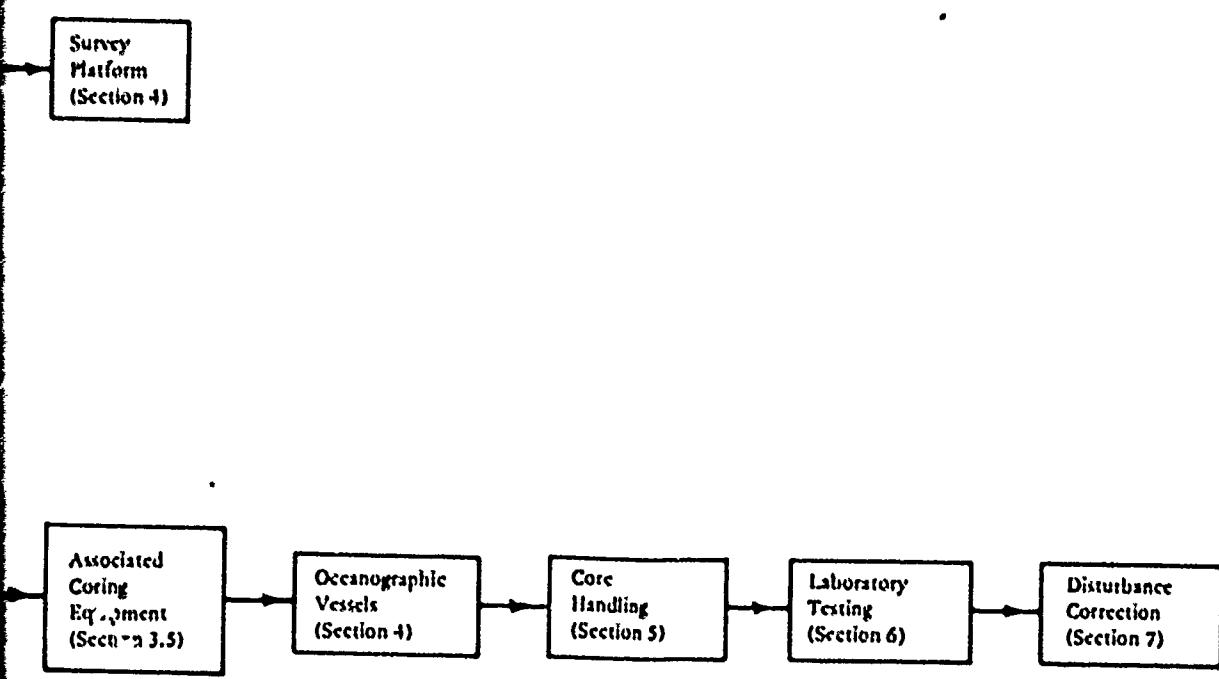


chart.

Table 1-2. Required Engineering Properties

Facility	Sediment	Soil Engineering Properties Required ^a	Subbottom Depth Range ^b
Embedment Anchor (including conventional drag anchors)	soft clay (cohesive)	S_u	(10 to 15 m) ^c
	stiff overconsolidated clay (cohesive)	$S_u, \bar{c}, \bar{\phi}$	(3 to 7 m) ^c
	sand (cohesionless)	$\bar{\phi}$	(4 to 10 m) ^c
Typical Downward Bearing Foundation (including clump anchors)	clay (cohesive)	S_u	1-1/2 to 2 times width of footing
	sand (cohesionless)	$\bar{c}, \bar{\phi}$	
Downward Bearing Foundation Sensitive to Deflection	soft clay (cohesive)	S_u, C_c, c_v	1-1/2 to 2 times width of footing
	stiff overconsolidated clay (cohesive)	S_u, C_c, C_s, c_v	
	sand (cohesionless)	$\bar{\phi}, C_c$	

^a S_u = undrained shearing strength (often referred to incorrectly as "cohesion")

\bar{c} = drained cohesion intercept

$\bar{\phi}$ = drained friction angle

C_c = compression index (slope of void ratio versus \log_{10} of compressive stress) for normally consolidated (usually soft) soils and overconsolidated soils at high loads.

C_s = recompression index (slope of void ratio versus \log_{10} of compressive stress) for overconsolidated (stiff) soils

c_v = coefficient of consolidation — the major parameter used in calculating settlement rates

^bProfile required from surface to depth given.

^cTo anticipated depth of fluke.

Section 2, NONPHYSICAL SAMPLING, describes fast methods for determining sediment properties approximately.

Section 3, PHYSICAL SAMPLING, discusses theoretical and practical aspects of different types of corers.

Section 4, SURVEY PLATFORMS, describes various types of ships that can be used to obtain sediment samples and identifies the organizations controlling the ships.

Section 5, CORE HANDLING, informs the user on how to handle, store, and transport cores.

Section 6, LABORATORY TESTING, presents a detailed discussion of the required sediment properties and the laboratory test procedures needed to determine them.

Section 7, DISTURBANCE CORRECTION, describes how strength measurements from laboratory tests can be corrected for sampling disturbance to give properties close to in-situ values.

Once the type of operation is decided and the necessary properties are delineated (Tables 1-1 and 1-2), the designer has to find the best method of determining those properties. Based on the quality of information needed, the user must decide on one of two options: Nonphysical or Physical Sampling. Schedules, cost, low risk, and design phase may determine that nonphysical sampling - perhaps merely a desk-top assessment - is all that is needed. Once this is fixed, Figure 1-1 can further be used to direct the engineer to the proper sections of this handbook.

Because costs are often the basis for choice among the options available to the design engineer, costs for many of the corers and ships are presented. Ideally, this document would present prices for each of the various methods of determining sediment properties, but the number of options for each type of operation is so large that it is impractical to try and present costs for each option. The following example is presented to illustrate this point (handbook section numbers are referenced for the convenience of the reader).

Example

The engineer is designing a foundation for a small platform. From reading Herrmann et al. (1972), the user decides shear strength and unit weight down to 3 meters (10 feet) are needed. Of the two constraining factors - time and money - money is assumed the most important in this example. The engineer must then decide whether or not the design can rely on the high safety factor inherent in the desk-top method (Section 2.1). If such is the case, the handbook can be put aside and the procedure is complete. If the safety factor associated with using approximate properties makes the design too expensive, a better method (Remote Sensing, Sections 2.2 or 2.3, or Penetrometer, Section 2.4) is needed. The designer now must select a particular method and must price various ship and equipment options (Section 4): Navy,

government, university (cooperative effort or sole user), or commercial ships and whether to rent or buy equipment. With this new information, the user has to decide if the methods produce an acceptable design; or, if they do not, can physical sampling be afforded (Section 3)? Physical sampling has many options: whether to buy, rent, or borrow a free-fall, box, short-gravity, short- or long-piston corer and, again, what type of ship (Section 4) can be used. If deep samples are needed (subbottom depths of greater than about 20 meters) or if much sand is present, drilling or percussion techniques must be used. These approaches are not considered in this handbook. The cost of testing the samples must also be considered.

Obviously, cost estimates are seen as only practical for the designer. The various constraints on the project should narrow the selection down to a few cost-effective approaches. This handbook is designed to make that process easier and quicker.

2. NONPHYSICAL SAMPLING

For seafloor facilities where a large risk factor is allowed or where designing with a large factor of safety costs less than a detailed site survey, rapid, less accurate techniques of property determination may be in order. These are discussed in this part of the handbook and include the following (in increasing order of cost and accuracy):

- (1) Typical properties are estimated, based on regional geology (Section 2.1) (Desk-top techniques)
- (2) Qualitative acoustic profiling (Section 2.2)
- (3) Quantitative acoustic profiling (Section 2.3)
- (4) Expendable penetrometer testing (Section 2.4)

2.1 DESK-TOP TECHNIQUES

Because the seafloor is primarily a depositional rather than an erosional environment, more uniformity of sediments and sediment properties can be found there than would be found on land. Properties based on known environmental conditions can often be estimated accurately enough for site selection and preliminary design. Even in more complex areas where a site survey is definitely required, an estimate of properties to be encountered will aid in designing the survey and influence initial thinking about the facility.

To estimate properties with some reliability, the designer must know some marine sedimentology. Fortunately, the basic concepts are simple. First, one must determine whether the sediments are land-derived (terrigenous) or ocean-derived (pelagic). Figure 2-1 gives an overall view of the ocean sediment distribution throughout the world.

2.1.1 Near-Shore Areas

One may assume that all continental shelves and slopes are terrigenous; also, virtually all seafloor features labeled "abyssal plains" have basically terrigenous components.* In a few areas of the world (North Atlantic or the far Northwest Pacific), other significant terrigenous deposits may well be found beyond the continental slope as a result of being downwind from major deserts. An engineer working in these areas should consult an expert from a nearby oceanographic institution for local information, the literature of marine geology, and ocean

*These were probably brought down by turbidity currents.

engineering research institutions such as the Civil Engineering Laboratory. This consultation should be for all areas and for all initial searches by ocean engineers with little background in geotechnology.

2.1.2 Deep Ocean Areas

The sediments of the deep ocean basins far from land are determined by two items: (1) sea surface biological productivity and (2) dissolution of calcium carbonate. Where productivity is high (such as the northern Pacific near the Aleutians, equatorial Pacific, and the region surrounding Antarctica), one finds siliceous ooze, a sediment composed of the remains of organisms whose hard parts are opaline silica. In those areas where calcium carbonate dissolution is less than the carbonate supply, calcareous ooze (a sediment composed of the remains of organisms whose hard parts are calcium carbonate) may be found. At water depths shallower than the calcite compensation depth (CCD), calcareous sediments are almost always found. The sediment is defined as a calcareous ooze if its calcium carbonate content is more than 30%; i.e., if it is not significantly diluted by terrigenous or siliceous materials. Generally, dilution by other materials is significant only near shore; on abyssal plains; and in the high productivity, siliceous ooze areas. The CCD has been mapped on a worldwide basis and is shown in Figure 2-2; one can determine whether calcareous ooze may be found by comparing the actual water depth with the CCD. Calcareous ooze typically becomes more coarse as water depth decreases (Figure 2-3). The equatorial Pacific typically has alternating bands of siliceous and calcareous ooze. Where biogenic (calcareous and siliceous) oozes are not found, one finds pelagic clay, an extremely slowly sedimented material composed primarily of wind-blown dust.

2.1.3 Terrigenous Sediments

Terrigenous sediments are the most complex and varied of the sediment types. The typical terrigenous material is probably a slightly plastic clayey silt; however, vast sand beds and some plastic clay deposits also exist. Layered deposits of sand, silt, and clay are common. Sedimentation rules are difficult to define. In a stable environment, grain size would decrease with distance from shore; however since dynamic processes are always active, this often does not occur. If the sea level is rising (e.g., off the east coast of the United States), one can almost assume that grain size will become finer near shore. For any particular location, an expert is probably available to estimate the types of sediments that can be expected. The charts of the National Ocean Survey* also provide estimates of sediment type although some of the classifications do not relate very well to engineering application (e.g., "brown mud"). However, the split between sand and clay or silt ("mud") appears reliable.

*Formerly U.S. Coast and Geodetic Survey, U.S. Department of Commerce.

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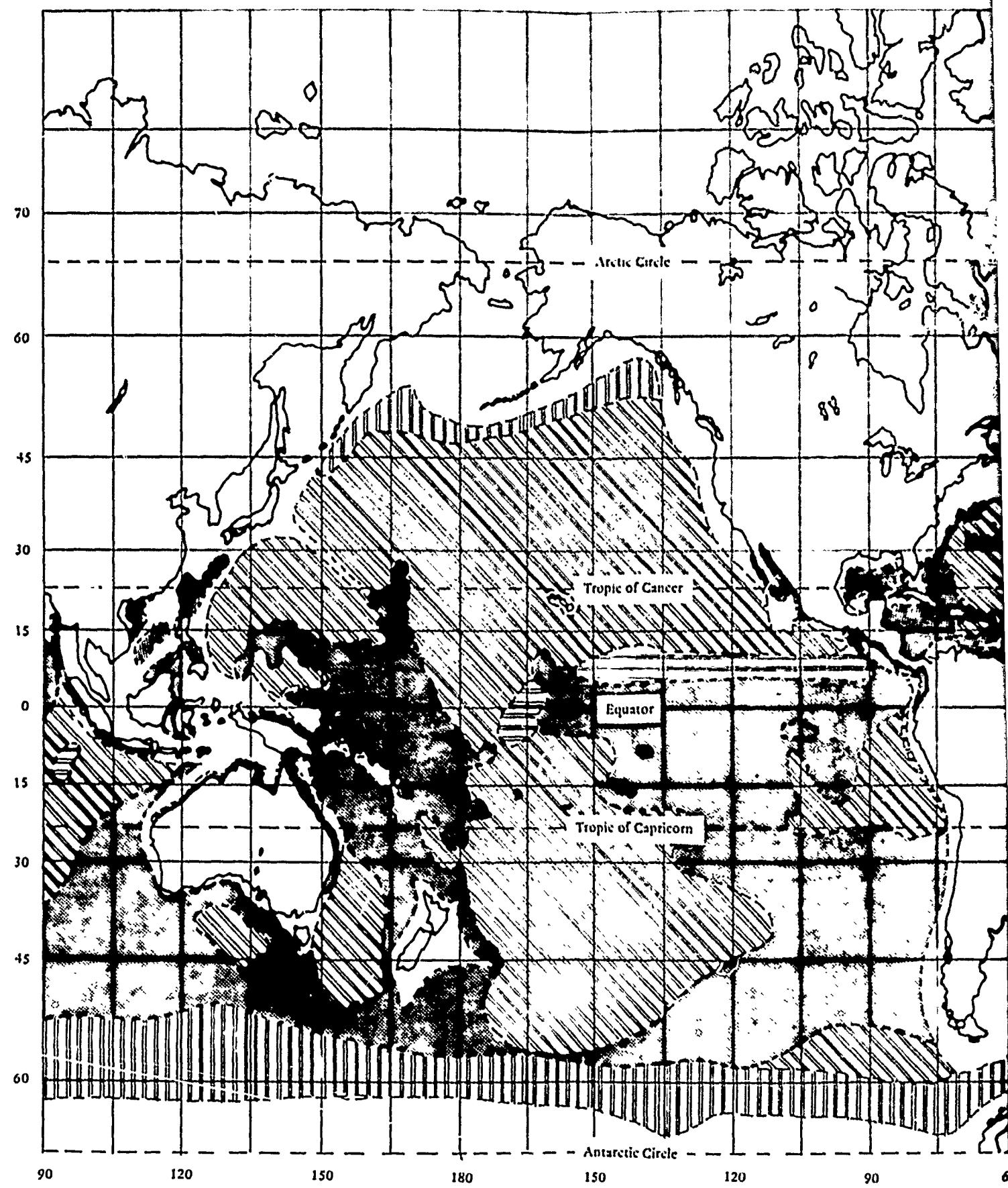
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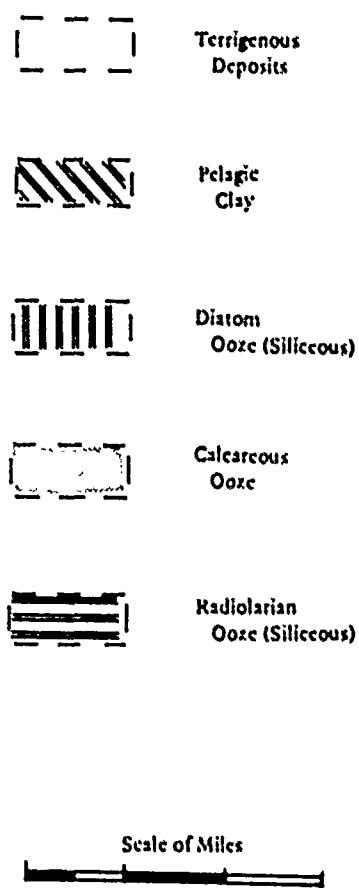
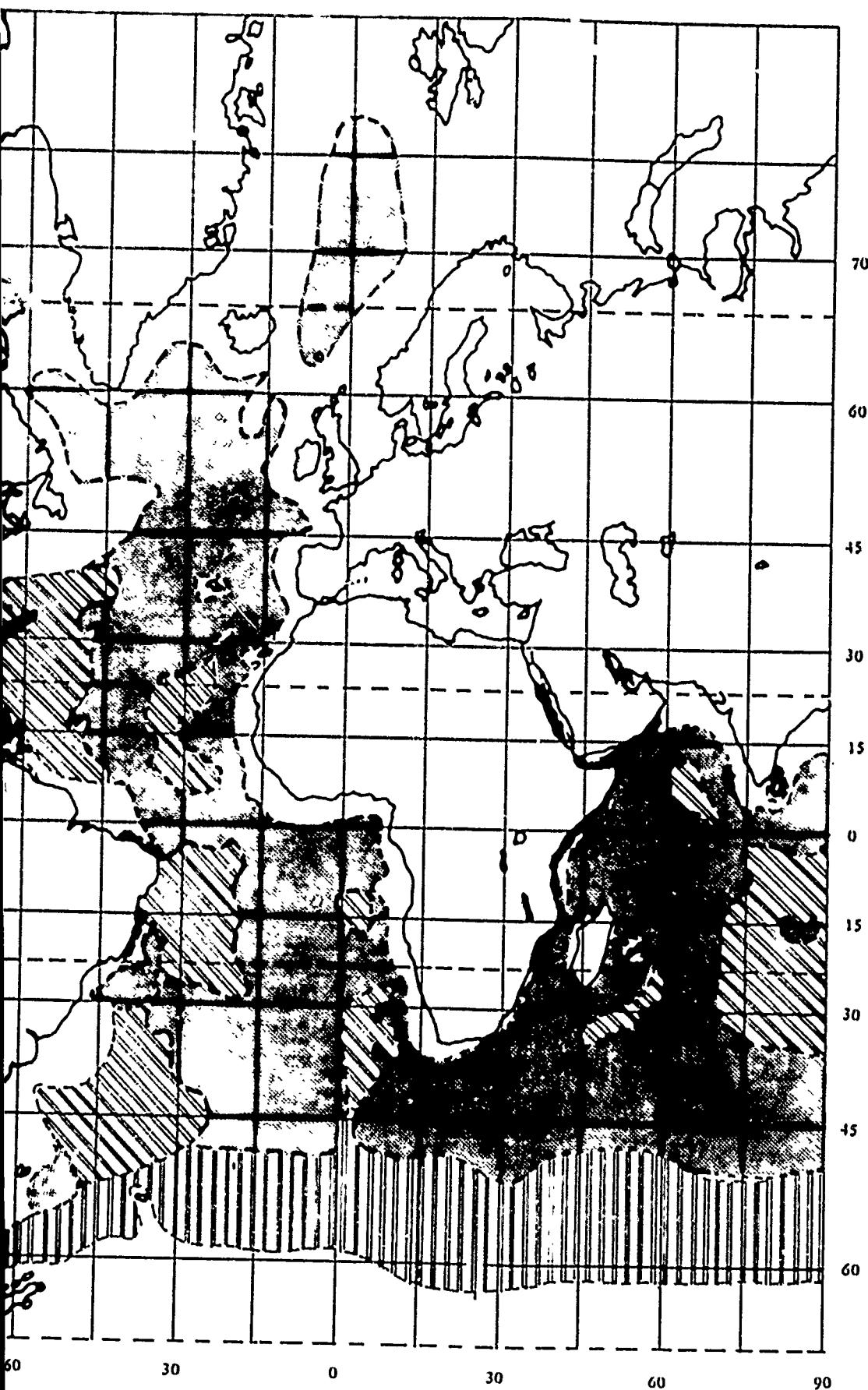


Figure 2-1. Ocean sediment distribution (H.

(Herrmann et al., 1972).

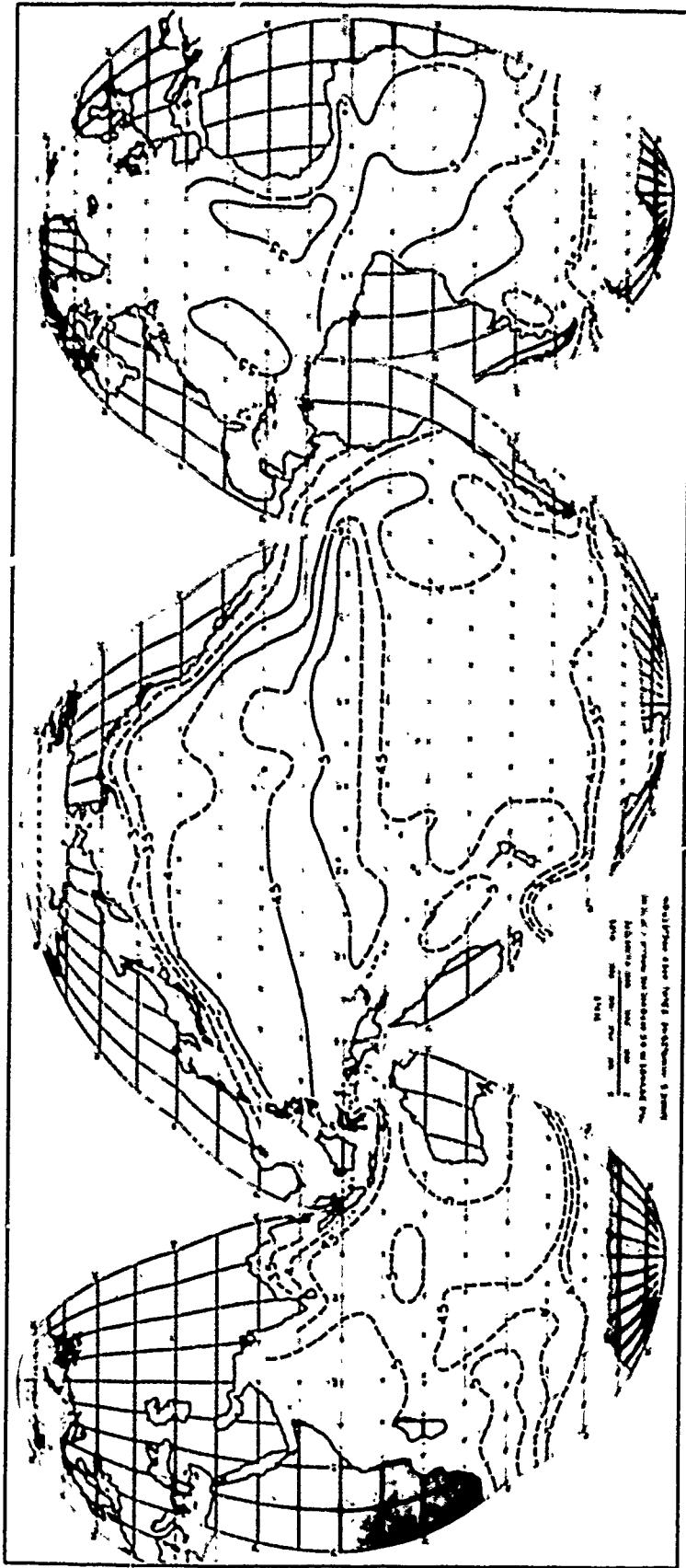


Figure 2-2. Topography of the calcite compensation depth (CCD). Calcareous sediments are found only in those locations where the actual water depth is less than the CCD; numbers on contours denote kilometers below sea surface (From Berger and Winterer, 1974).

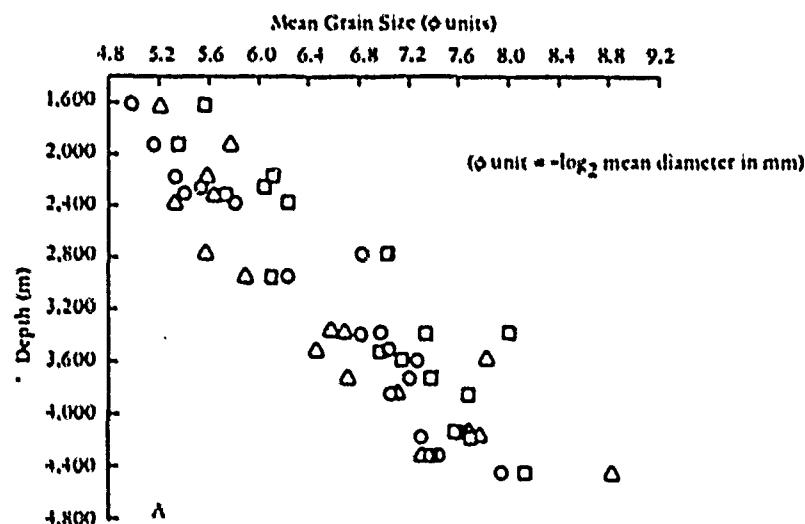


Figure 2-3. Mean grain size of carbonate sediment samples versus depth of deposition (from Johnson, Hamilton, and Berger, 1977).

Sediment classification on the basis of grain size or origin may not be adequate for engineering application. The design engineer should also know something about the state of the sediment. For cohesive sediments, three terms are important: (1) overconsolidated, (2) normally consolidated, and (3) underconsolidated.

Normally consolidated sediments are the rule in the deep ocean; these are materials that have never been loaded by overlying material more than they are now. Overconsolidated sediments have had a greater load (overburden) in the past and have since lost it by chemical processes or mechanical erosion. Underconsolidated sediments are young and have not come to equilibrium with the weight of overlying material.

If one assumes all deep ocean sediments to be normally consolidated, one will usually be correct and conservative. A few important exceptions do exist, but these need not concern the engineer unless finding an unusually strong (overconsolidated) sediment would lead to a less conservative design.

Much of the near shore is overconsolidated. Since this is usually a desirable situation and since it is so common, it would be valuable to find overconsolidated locations and determine their overconsolidation level.* There are no fast rules for locating overconsolidated sediments except that exposed locations (tops of rises, passages) are more likely to be overconsolidated than are protected locations (basins).

Underconsolidated sediments are almost always found in active river deltas such as that of the Mississippi River. If deposition is fast enough, there may be almost no buildup of strength with subbottom depth. If one is operating near the mouth of a river such as the

*Overconsolidation ratio (OCR).

Mississippi, Amazon, or Nile, one should be prepared for unusually weak sediments and never rely on typical property profiles. Other areas of underconsolidated sediments include embayments that exhibit high depositional characteristics with low water velocity.

2.1.4 Sediment Property Selection

With this brief background as a basis, it is recommended that the designer use the following procedure for selecting typical sediment strength, density, and sensitivity data.

(1) If the site is on the continental shelf or slope, the sediment is assumed terrigenous. Available National Ocean Survey charts are consulted to determine whether the sediment is primarily sandy or cohesive ("mud"). If the sediment is cohesive, Figure 2-4, which gives a lower bound for the strength distribution for a normally consolidated sediment, is referred to. A search for strong indications of overconsolidation is made: recorded outcrops of older sediments, exposed location (rise top, high recorded bottom currents). If sufficient evidence exists to suspect overconsolidated soils (e.g., vicinity of rise top, high recorded bottom currents, and eroded surface), it would be prudent to drop some penetrometers or short gravity corers. However, the engineer should be aware that both of these devices will not penetrate deeply into highly overconsolidated sediment. Nonpenetration or slight penetration with attainment of minimal sample length can add credence to the suspicion that overconsolidated sediment does indeed exist. Typical sand properties are given in Figure 2-5; sand exploration techniques will be considered in a later document. If the location is near a large active river delta, the site must be surveyed directly.

(2) If the site is in the deep ocean and not on an abyssal plain, it is determined whether its water depth lies above or below the CCD (Figure 2-2).

(a) If above, the sediment is probably calcareous ooze. Figure 2-6 gives the typical properties; it should be noted that a further subdivision between coarse and fine ooze is made at the 3,000 meter (10,000 foot) level.

(b) If the site is below the CCD the sediment is probably pelagic clay. Figure 2-7 shows the typical properties.

(3) If the location is identified on physiographic province charts as an abyssal plain, the typical properties (classed as turbidite) shown in Figure 2-5 are assumed. A split is made between proximal and distal turbidites. The distance from a source of sand (the shore or perhaps the edge of the continental shelf) distinguishes the two: if the distance is greater than about 50 km (30 miles), the sediment is probably a distal turbidite.

(4) If the location is classed as a siliceous ooze (diatom or radiolarian ooze, Figure 2-1), the typical properties can be found in Figure 2-8.

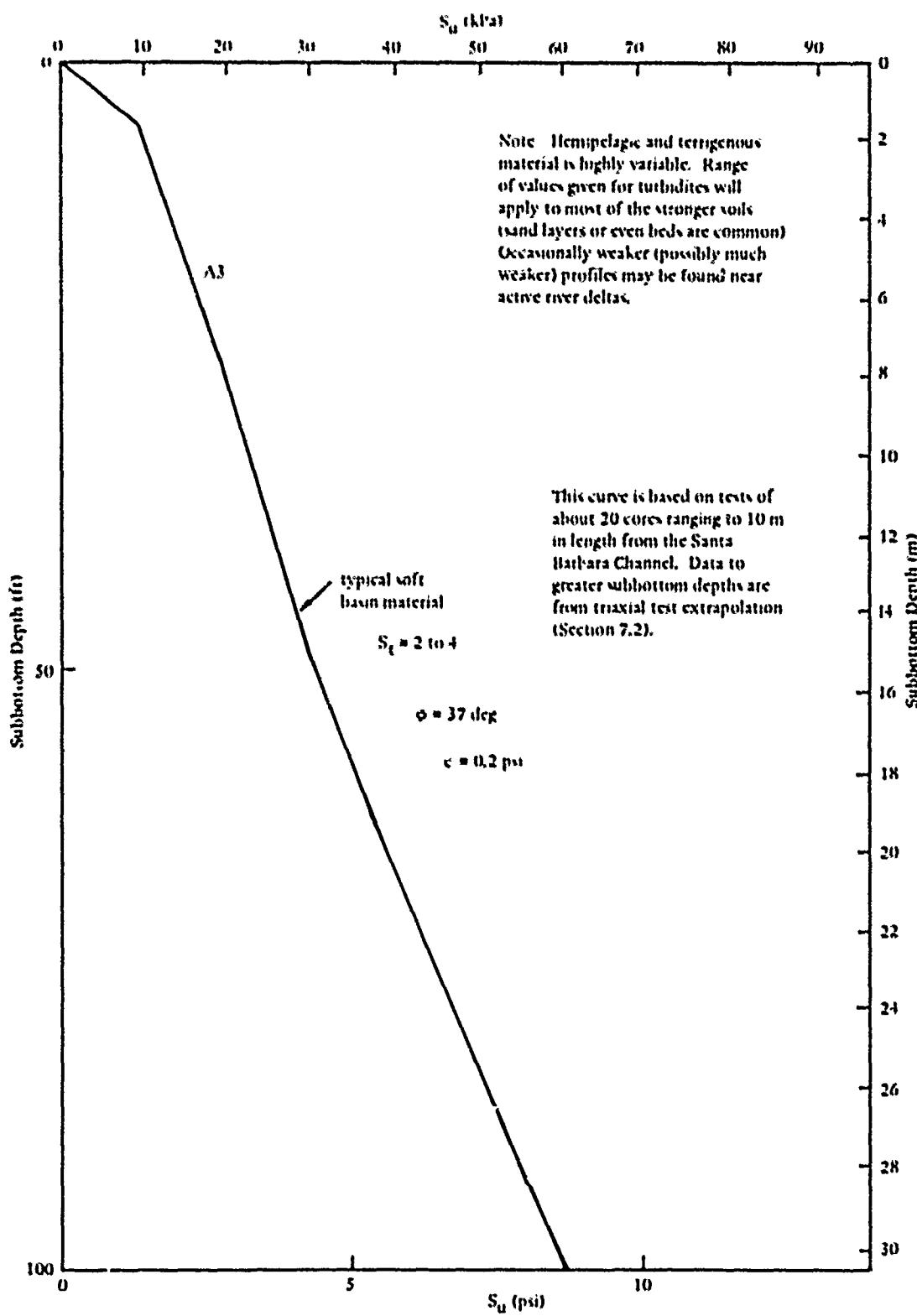


Figure 2-4. Typical strength profile, hemipelagic, terrigenous silty clay.

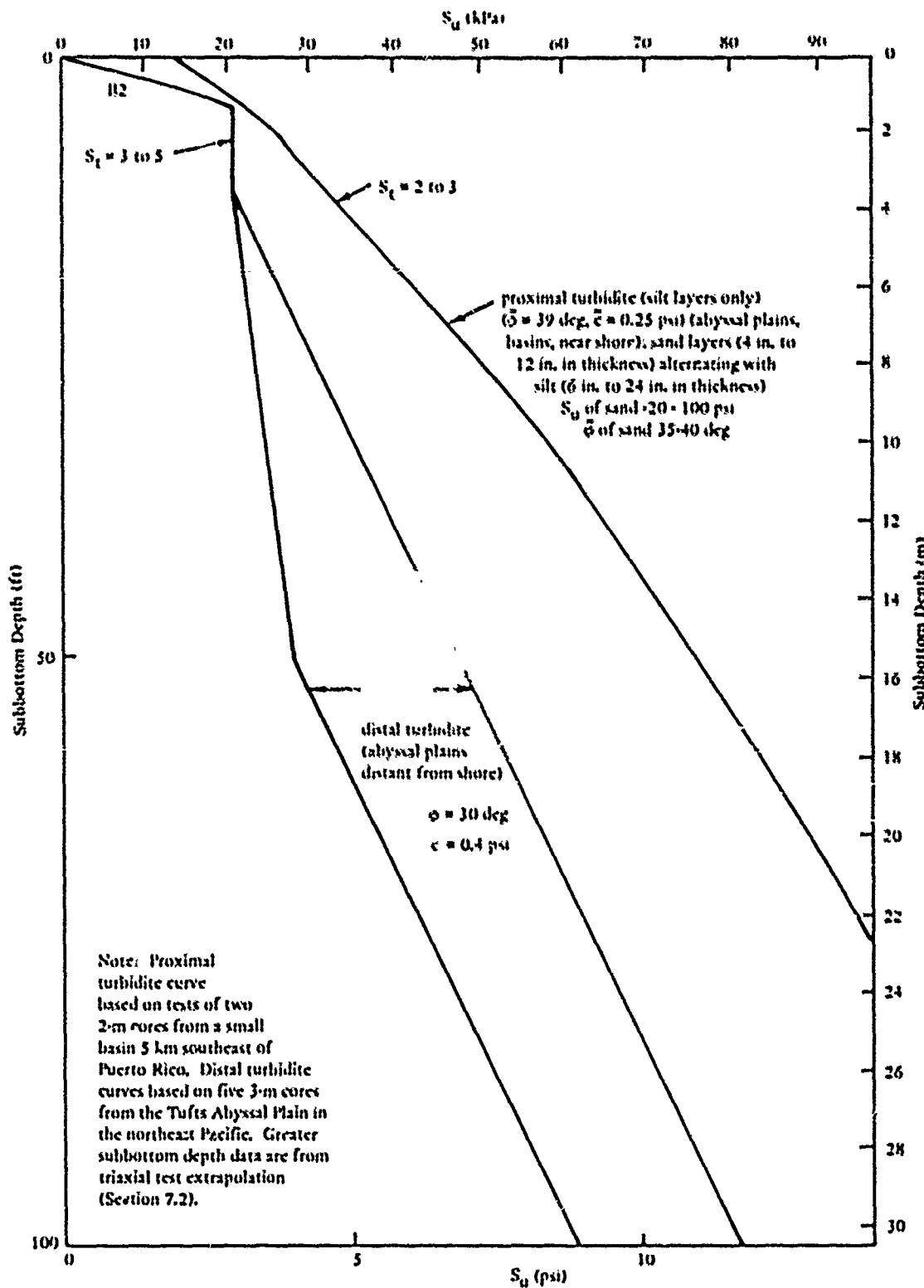


Figure 2-5. Typical strength profiles, turbidites

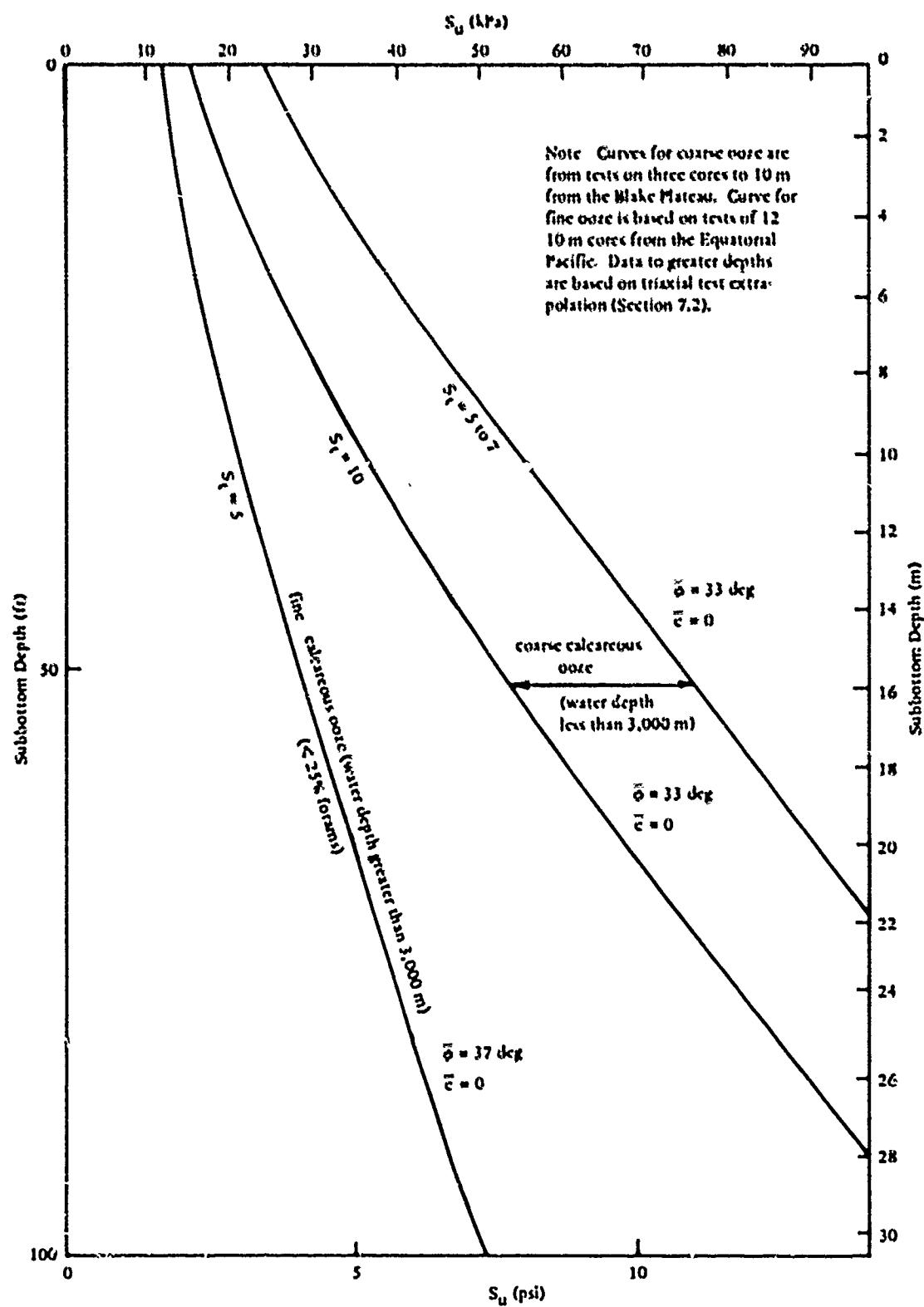


Figure 2-6. Typical strength profiles, calcareous ooze.

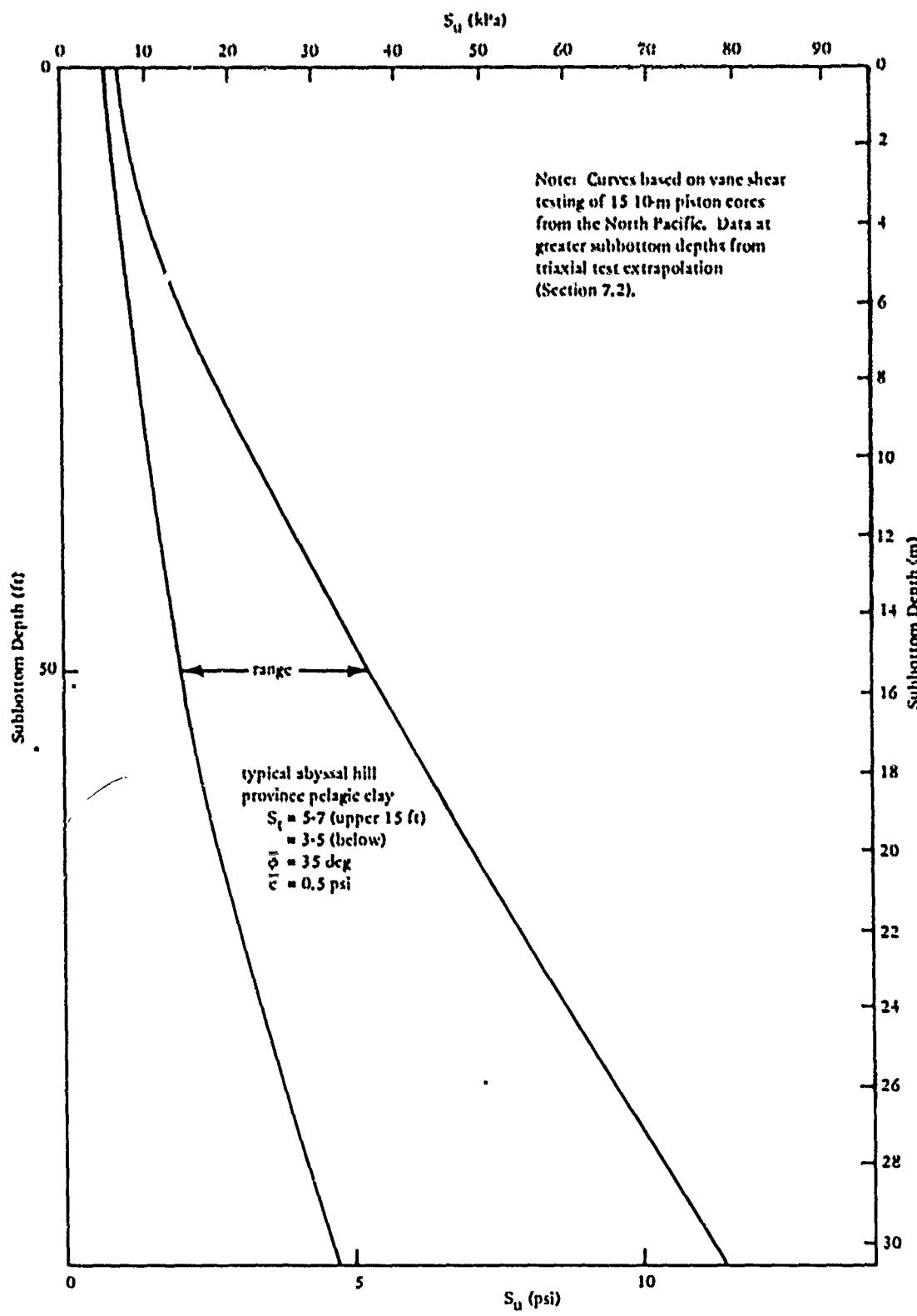


Figure 2-7. Typical strength profiles, pelagic clay.

(5) Whenever possible, the local experts at oceanographic institutions should be consulted. Many parts of the seafloor have been mapped for sediment distributions, and much more detailed information than can be given in this discussion may be available. Many core sample descriptions are available through the National Geophysical and Solar-Terrestrial Data Center, Environmental Data Service, National Oceanic and Atmospheric Administration, Boulder, CO 80302.

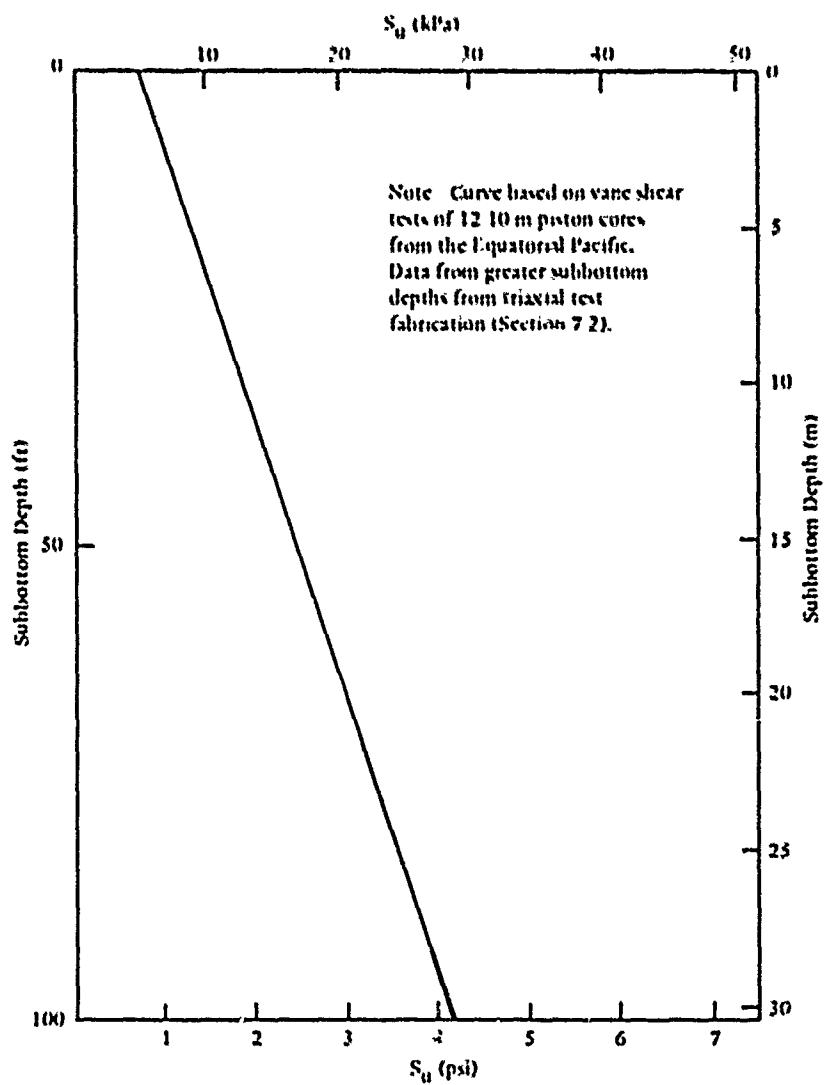


Figure 2-8. Typical strength profile, siliceous ooze.

2.2 QUALITATIVE ACOUSTIC PROFILING

Much of the seafloor has been profiled acoustically by the Navy, oceanographic institutions, and other organizations. Often, the information obtained by these groups is available through the National Geophysical and Solar-Terrestrial Data Center. For areas not already covered, it is relatively simple to obtain new data. Virtually all oceanographic vessels are equipped with the necessary electromechanical sound sources and receivers to routinely perform 12- and 3.5-kHz profiling. If a vessel discussed in Section 4 can be obtained, then profiling can be done with the assistance of the shipboard electronics technician. The slower the ship speed the higher will be the quality of record obtained. Speeds of 2.5 m/sec (5 knots) or less are usually recommended; however, records obtained at 5.0 m/sec (10 knots) are often found to be satisfactory.

A frequency of 3.5 kHz is usually best for soil mechanics work. Penetration of 20 meters (65 feet) or more is usually obtained while near-surface resolution is retained as well.

A subbottom acoustic profile appears to give a cross section of the strata beneath the seafloor. However, it is really a plot of the time it takes for sound to pass from a ship to a reflector and back again versus clock time. An ideal profile is obtained if:

- (1) The spacing of sound pulses is always the same, pulses are short, and little drift in the electronics is experienced.
- (2) The speed of sound in water and sediments is the same and constant.
- (3) The ship travels at constant speed and heading.
- (4) Reflection occurs only from points directly beneath the ship.

An ideal can also be obtained if corrections can be made for deviations from these items. Item (1) is usually satisfied by modern profiling systems.

Item (2) is never true; however, assuming it is true is good for a first approximation for shallow subbottom depths. Most recorders are set assuming a sound speed of 1.5 km/sec or 4,800 fps. These values are close to what the real values probably are. If more accuracy is needed, one can refer to Matthew's Tables (Matthews, 1927) for water and Hamilton (1974) for sediments.

Item (3) can be satisfied approximately if care is taken. If reliable navigation systems are used, corrections can be made for variable speeds and headings.

Item (4) may be a serious problem in rugged areas where sound usually reflects from high points not beneath the ship. With experience, one quickly learns to identify the inverted hyperbolas that result from side echoes. Unfortunately, the record of sound reflecting from surfaces directly below the ship may be lost or difficult to identify.

Even if the seafloor is not extremely rugged, echoes from points not beneath the ship cause slopes to appear less steep and falsely represent the seafloor topography. Multiple reflections (sound reflected back from the sea surface to the seafloor and back to the ship again) may appear as false layers. Gating (listening to sound only during pre-selected periods based on water depth) removes some multiple reflection problems; in shallow water, however, it is difficult to gate.

The interpretation of subbottom acoustic profiles is still very much an art. An experienced marine geologist or geophysicist should be consulted to obtain an opinion of the type and condition of sediments indicated by subbottom profiles.

Some attempts have been made to standardize the interpretation of acoustic profiles (see Table 2-1). The appearance of each of the echo types is given in Damuth and Hayes (1977). Sediment beds can be separated into about three classes (see Table 2-1, Types IIB, IIA, and IIB), each with a differing amount of coarse sediment present. Also outcropping rock zones (Type IIIA) and a variety of bedforms (Types IIIB through IIIF) can be located that may be diagnostic of bottom current conditions. This tentative standardization is provided only as an indication of the type of assessment that can be made of acoustic profiles. Unless the user has experience in interpretation, consultation with an experienced marine geologist is almost mandatory.

With these profiling and interpretation methods it may be possible to separate sandy and clayey deposits, and this information could be quite valuable in nearshore terrigenous deposits. The level of accuracy that can be obtained probably varies directly with the skill and experience of the interpreter.

In addition to rough classification, acoustic profiling can provide some information on overconsolidation. Since overconsolidation involves the removal of overburden, it may appear as truncated or outcropping reflectors. Beds with regular reflectors parallel to the seafloor would be less likely to be overconsolidated and, therefore, weaker.

2.3 QUANTITATIVE ACOUSTIC PROFILING

Quantitative acoustic profiling would involve obtaining geotechnical properties information directly from the quantitative character of the reflected acoustic pulses. Within the present state-of-the-art, usable engineering information is not obtained. Future research may produce viable survey techniques that use this approach.

2.4 PENETROMETERS

Objects colliding with the seafloor are subjected to forces which are derived in part from the shearing resistance of the sediment. Several organizations have developed devices designed to penetrate the seafloor to as much as 15 meters (50 feet) and measure motion data that can be analyzed in terms of penetration forces and shearing strengths.

Table 2-1. Classification of Acoustic Echo Character^a

Echo Type	Echo Characterization	Sediment Correlation
I. Distinct Echoes		
A	Sharp continuous, without subbottoms	Thin cover of sand and gravel over consolidated sediments (sedimentary rock)
B	Sharp continuous, with numerous parallel subbottoms	Minor amounts of bedded coarse sediment
II. Indistinct Echoes: Prolonged		
A	Semiprolonged (mushy), with intermittent parallel subbottoms	Low to moderate amounts of coarse sediment
B	Very prolonged, without subbottoms	Large amount of bedded coarse sediment
III. Indistinct Echoes: Hyperbolas		
A	Large irregular hyperbolas, with varying vertex elevation	Very rugged seafloor; perhaps with outcropping basalt
B	Regular single hyperbolas, with varying vertices and conformable subbottoms	Large sediment waves; may be pelagic clay, terrigenous clay-silt, or distal turbidites
C	Regular overlapping hyperbolas, with varying vertex elevations	Regularly spaced erosional/depositional bed forms; may be pelagic clay, calcareous ooze, or terrigenous clay
D	Regular overlapping hyperbolas, with vertices tangent to seafloor	Small, regular bed forms; may be homogeneous pelagic clay or calcareous ooze
E	Type IIIID hyperbolas with intermittent zones of distinct Type IIB echoes	Small, regular bed forms; may be homogeneous pelagic clay or calcareous ooze
F	Irregular single hyperbola with non-conformable subbottoms	Active erosion and redeposition

^aAfter Damuth and Hayes, Lamont-Doherty Geological Observatory of Columbia University, 1977.

A representative penetrometer is the CEL Expendable Doppler Penetrometer (Figure 2-9). The device is a small-diameter (89 mm, 3.5 inch), 2.44-meter (8-foot) long, lead-weighted tube with spherical nose and tail fins. Its terminal velocity is about 30 m/sec, and it penetrates up to 15 meters (50 feet). It produces a continuous sound signal at a constant 12-kHz frequency. The frequency of sound received at a surface ship is related directly to the penetrometer velocity through the Doppler principle. The changing velocities that indicate the penetrometer slowing down as it enters the seafloor are differentiated to obtain deceleration values: net force on the penetrometer is the penetrometer mass times the deceleration.

A number of techniques have been developed to convert total penetration force to sediment shear strength. They involve splitting up the force into various components which correspond to different elements of an assumed mode of soil failure. An example given by Beard (1977) is as follows:

$$F_T = W' - F_{BE} - F_{AD} - F_H \quad (2-1)$$

where F_T = total force (positive downwards)
 W' = weight of penetrator submerged in sediment
 F_{BE} = force on nose of penetrator = $S_e (S_u N_c A_n)$
 S_e = strain rate effect (varies between 1 and 2 as a function of velocity)
 S_u = undrained shear strength of sediment
 N_c = bearing capacity factor (usually 9)
 A_n = frontal area of nose
 F_{AD} = force on side of penetrometer = $S_e (S_u \delta A_s / S_t)$
 δ = side adhesion factor (often assumed equal to 1)



Figure 2-9. CEL Expendable Doppler Penetrometer - a device for measuring sediment shear strength in place through the deceleration of a penetrating object.

A_s = side area
 S_t = sediment sensitivity (must be assumed on the basis of estimated sediment type)
 F_H = inertial drag = $1/2 \rho C_D A_N V^2$
 ρ = sediment density
 C_D = drag coefficient (assumed to be the same as that in water and can be calculated from the measured terminal velocity)
 V = penetrator velocity

This equation is usually solved iteratively by a computer* to convert a deceleration-depth profile into a strength-depth profile.

The accuracy of the resulting strength estimates is somewhat dependent upon the choice of S_t in the calculations. If S_t is known exactly (perhaps from tests on one core taken in the same sedimentary formation), then strength accuracies of $\pm 30\%$ can be expected. If S_t must be estimated from general assumptions about sediment type, the accuracy of strength estimates may degrade to $\pm 50\%$.

*Computer programs for this reduction are available from CEL.

3. PHYSICAL SAMPLING

The physical samplers discussed in this section are of four types: box corers, free-fall corers, short-gravity and -piston corers, and long-piston corers. Box corers take short (0.6 meter), large volume, undisturbed samples. Free-fall corers do not require a winch and wire and can take samples in exact locations. Short-gravity and -piston corers are inexpensive, reliable devices that take samples up to 3 meters (10 feet) long in diameters up to 67 mm (2.6 inches). Long-piston corers take samples from 3 to 40 meters (10 to 130 feet) in length and up to 120 mm (4.7 inches) in diameter. The common maximum length of a piston corer is 15 meters (50 feet). Drilling and percussion methods are not discussed.

This coring procedure discussion is not intended to be complete in this document but, instead, to complement each particular corer's instruction manual by offering information not included in most manuals. People experienced with corers are necessary for successful operation, particularly with long-piston corers. The section in this handbook on box corer procedures has more information than for the other corers because not as many people are familiar with this piece of equipment.

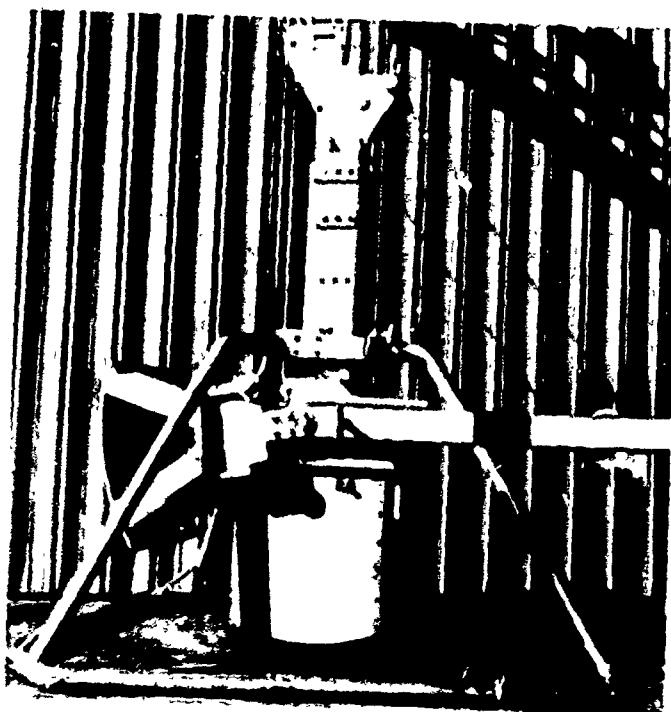
Accessories are important in the operation, and those most often associated with coring are winches and wire, pingers, releases, terminations, and liners. Where to obtain coring equipment is included as a part of this section.

3.1 BOX CORERS

3.1.1 Description

The most important advantage of box corers is the large volume, nearly undisturbed sample they take. A summary of box corer characteristics is presented in Figure 3-1. Box corers take short, 0.61-meter (24-inch), large surface area cores. Standard box sizes are 0.025 (0.28), 0.1 (0.67), and 0.25 sq m (2.78 sq ft). Box corers consist of a weight column, sample box, spade lever arm, and a tripod support frame (see Figure 3-2).

The operation of a box corer is fairly simple. As Figure 3-2 shows, the box corer is lowered in the cocked position. After the support frame contacts the seafloor, the weight column drives the box into the sediments. When line is taken in, the spade is rotated to a vertical position which prevents the sample from falling out. As more line is taken in, the box is pulled out of the sediments, and the whole unit is returned to the ship.



Item	Small Version	Large Version
Corer Dimensions		
Long x wide x high, m	0.75 x 0.65 x 1.5	2.03 x 1.73 x 2.15
Long x wide x high, in.	29 x 26 x 60	80 x 70 x 85
Corer Weight		
kN	2.0	4.4 to 7.1
lb	460	1,000 to 1,600
Sample Size		
Long x wide x high, m	0.25 x 0.1 x 0.3	0.3 x 0.2 x 0.6
Long x wide x high, in.	10 x 4 x 12	12 x 8 x 24
Long x wide x high, m		0.5 x 0.5 x 0.6
Long x wide x high, in.		20 x 20 x 24
Ship Requirements	Winch, A-frame, and capstan; or winch and movable A- or U-frame	
Wire	Capable of supporting the box corer and wire with an acceptable safety factor	
Accessories	Pinger, precision depth recorder (PDR), swivel, extra boxes	
Price	\$1,500	\$4,200 to \$9,000
Manufacturers	Kahl Scientific Instrumentation Corp. ^a	Ocean Instruments ^a

^aSee Appendix B for address.

Figure 3-1. Summary of box corer characteristics.

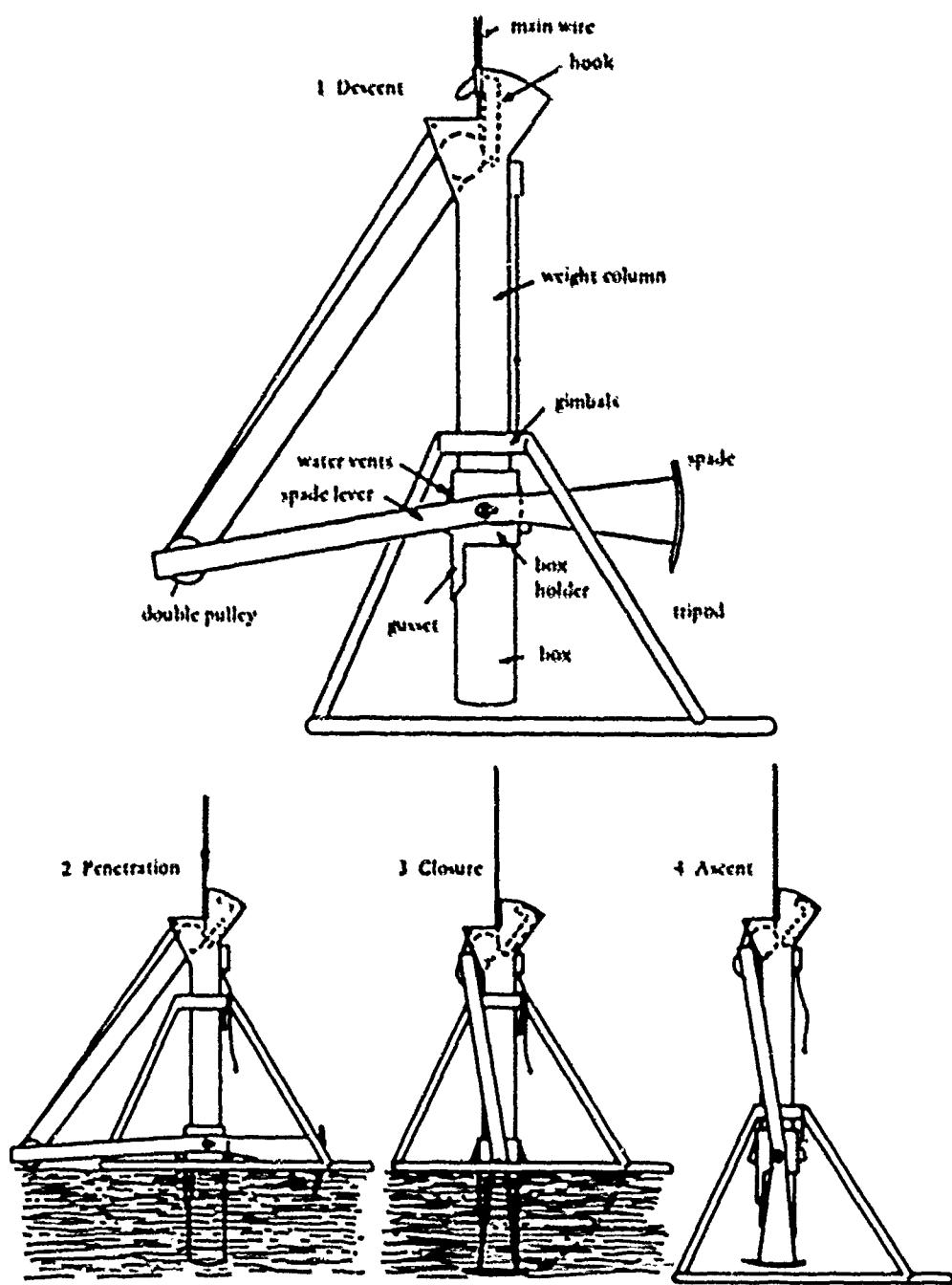


Figure 3-2. Box corer — parts and operation sequence (reprinted by permission of the University of Illinois Press, publishers of "Obtaining large, undisturbed, and orientated samples in deep water," by Andre M. Rosfelder and Neil F. Marshall, from the book entitled *Marine Geotechnique*, Adrian F. Richards, editor, 1967. © 1967 by the Board of Trustees of the University of Illinois).

The small version of the box corer is impractical for strength measurements because it can only sample down to 0.3 meter (1 foot). Therefore, the discussion on box coring will be confined to the characteristics of the large version manufactured by Ocean Instruments. Ocean Instruments makes three models of box corers:

<u>Model No.</u>	<u>Description</u>	<u>Corer Price</u>	<u>Box Price</u>
MK-1	0.10 sq m (8x12x24 in.), side venting	\$4,200	\$160
MK-2	0.25 sq m (20x20x24 in.), side venting	\$5,400	\$260
MK-3	0.25 sq m (20x20x24 in.) Hessler-Sandia type, automatic top venting	\$9,000	\$260

Past models of box corers were very prone to pretrip on the way down. A pretrip occurs when dynamic motion causes the box corer to become temporarily weightless and to release the hook. When the tension returns, the spade is pulled up to the vertical position. New models come with a pretrip preventer. The newer models, with their pretrip preventers, offer a fairly high success rate in seas up to 6 feet; however, the box corers will pretrip in 6 to 10-foot seas a significant portion of the time, even with the pretrip preventers. This is especially true when using the box corer off the stern of smaller ships. Box coring in seas over 10 feet is not practical because of the probability of a pretrip and the problems associated with safely handling the box corer.

A new type of box corer was developed by Selwyn (1978) of the Lamont-Doherty Geological Observatory (Figure 3-3). The corer takes a sample 0.46 meter (18 inches) on each side and 1.83 meters (6 feet) long. This box corer is attached to the weight stand of a conventional corer weighing at least 7.6 kN (1,700 pounds). This box corer reportedly works well, does not have the pretripping problem of conventional box corers, and is inexpensive (\$2,000 in 1978). Based on these features and the length of the sample, the Lamont box corer appears to be very good for detailed strength measurements of the upper 1.83 meters (6 feet) of sediment.

3.1.2 Procedures

The basic procedures for using box corers are as follows. First, the box corer is assembled according to the manufacturer's instructions. Then the box corer is moved under the "A" or "U" frame. A rope fair-leaded to a capstan is usually the way box corers are moved. Two tag lines are put around the legs of the box corer, which is lifted off the deck with the winch. The pins that support the weight section are

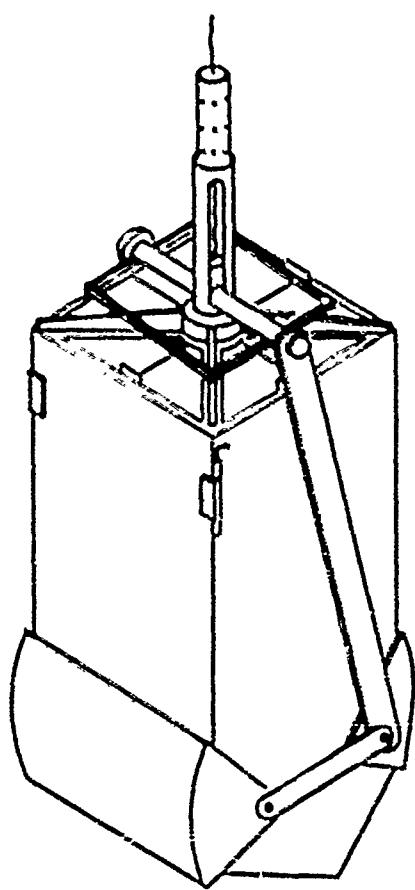


Figure 3-3. Lamont box corer (Schwyn, 1978).

removed and put in a safe place. The box corer is swung out and lowered into the water. Once the base is in the water the taglines can be removed. A pinger (usually 12 kHz) should be used to show the position of the box corer relative to the bottom. Standard practice is to place the pinger from 15 to 30 meters (50 to 100 feet) above the box corer. A mark or two should be made on the wire with spray paint 30 to 60 meters (100 to 200 feet) above the pinger to alert the winch operator to the corer position when the box corer is retrieved.

Safe lowering rates for the box corer depend on the seas. In calm seas - less than 1 meter (3 feet) - 60 m/min (200 fpm) is a safe maximum rate. In rough seas - greater than 2 meters (6 feet) - 30 m/min (100 fpm) is a safe maximum rate. In calm seas, the rate of descent may be slowed to 15 m/min as the box corer approaches the bottom to allow the corer to stabilize; but, in rough seas, the rate of descent should remain constant as the box corer approaches the bottom to prevent pretripping.

Once the box corer is on the bottom the winch should be stopped to prevent excess line from paying out. If the winch is not stopped, the excess line may get tangled on the box corer and prevent its closing or may flip the corer over when the line is retrieved. Also, the pinger can be damaged if it drags on the bottom or hits the box corer.

The line can be retrieved as fast as is safe for the winch. A person is stationed to watch for the wire marks when the box corer and pinger get near the surface. The pinger is removed from the wire after it surfaces. Once the box corer surfaces, tag lines are put on as soon as possible (Figure 3-4). Swinging of the box corer can be reduced by joining tag lines with a safety snap and pulling against the main wire at a point above the box corer, thereby lowering the fulcrum point. Pins have to be inserted before the corer is set down on the deck. A hammer is helpful to push the pins all the way through. Once the pins are inserted, the box corer is set down on the deck; however, tension must be kept on the line to prevent the spade from falling down. A strong rope should be tied around the spade before tension is released. Then the bottom is put on the box, the rope holding the spade untied, the spade opened, and the box core removed.

If the box of sediment is large, it can weigh 2.2 kN (500 pounds) or more. Man-handling something this size is very difficult; therefore, a small cart can be very useful when handling box cores.

Box corers are easy to maintain; most of the important parts are stainless steel. Hosing it down with freshwater and lubricating the moving parts should be sufficient to keep the box corer in working order. Because dynamic effects tend to vibrate loose the bolts, they should be checked after each lowering.

3.2 FREE-FALL CORERS

3.2.1 Description

The only free-fall corer commercially available is manufactured by Benthos, Inc., and is called the "Boomerang" corer (Figure 3-5). This corer is unusual because it is not lowered on a wire to the seafloor. Instead, it free-falls to the ocean bottom. After impact, a float is released that pulls the core liner out of the barrel and returns the sample to the surface. The major advantages of the Boomerang corer are its ability to take cores in a relatively exact location and the speed with which a core can be taken. The major disadvantage is the shortness of the core.

The parts and sequence of operation of the Boomerang corer are shown in Figure 3-6. The ballast portion, which is lost on each core, consists of a steel barrel, cast iron weight, steel float protection, and lead pilot weight. The float portion, recoverable and reusable, consists of the core liner, valve release, and two glass spheres.

During deployment a hollow rubber ball prevents the glass spheres from releasing should the pilot weight slide up the barrel (1).* Once in the water the corer quickly rights itself and accelerates to its terminal velocity of 450 m/min (1,476 fpm) in about 20 meters (66 feet). Hydrostatic pressure compresses the ball, releasing it, and freeing the float release lever. When the corer impacts, the pilot weight slides up the barrel (2) allowing the float lever release to pivot and release the glass floats (3). As the glass floats ascend, they pull the plastic liner out of the barrel (4) and close the valve release at the top of the liner which seals the top of the sample. The glass floats rise to the surface at 75 m/min (246 fpm). Upon reaching the surface the electronic flash inside one of the glass spheres begins to flash once every two seconds. When the flash is sighted, the ship is brought alongside and the unit is recovered.

*These numbers refer to Figure 3-6.

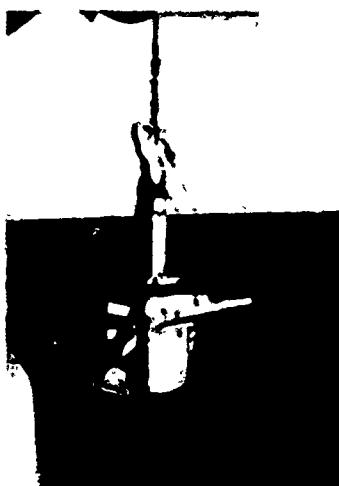
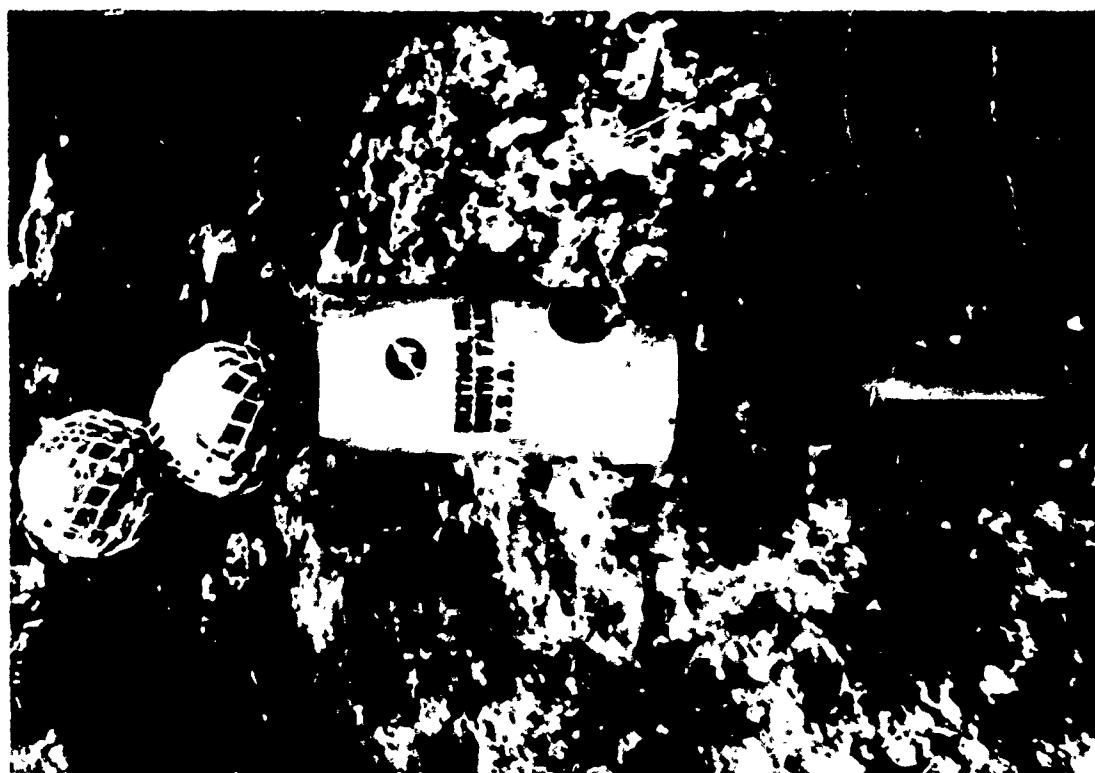


Figure 3-4. Large box corer being deployed over the side of a ship.

Characteristics	Value
Corer Overall Length	2.03
m	2.03
in.	80
Weight	0.67
kN	0.67
lb	150
Sample Length	1.2
m	1.2
in.	48
Sample Diameter	6.5
mm	6.5
in.	2.56
Ship Requirements	None
Accessories	None hook
Price (1978)	
Complete Unit	\$970
Expendible Buoyant Unit	\$25
Reusable Float Unit	\$65
Manufacturer	Benthos, Inc.

Figure 3-5. Summary of free-fall corer characteristics
(courtesy of Benthos, Inc.).



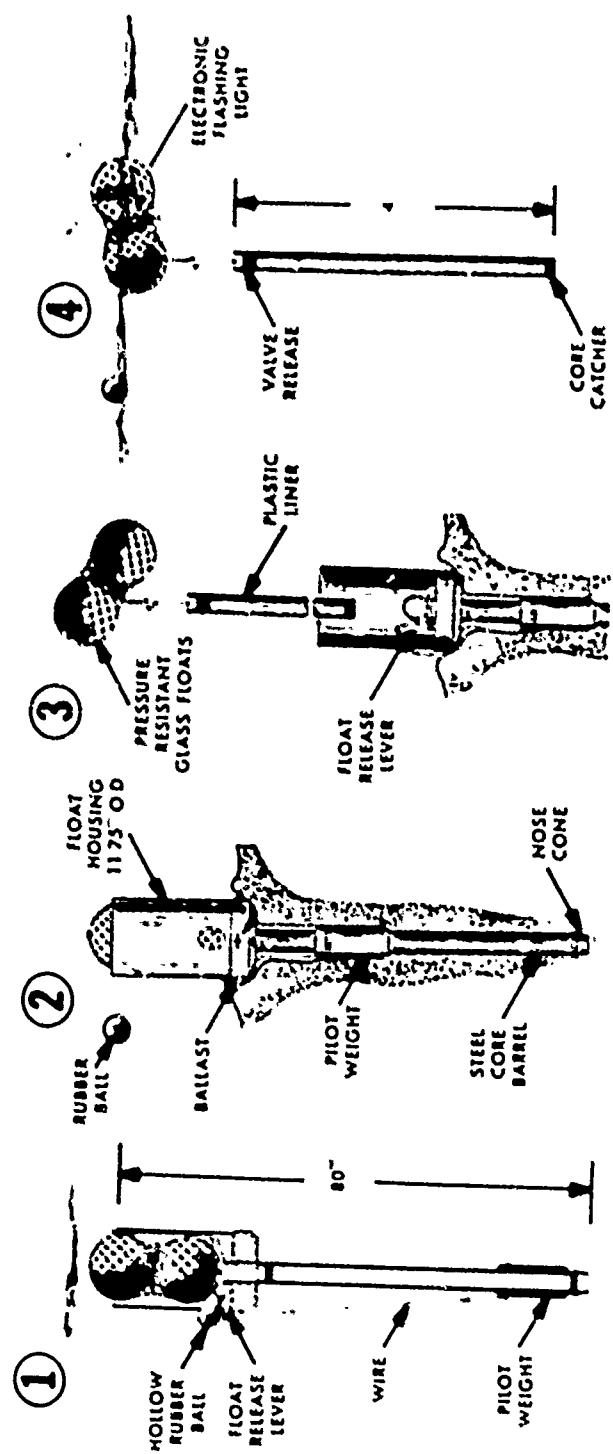


Figure 3-6. Boomerang corer parts and sequence of operation (courtesy of Benthos, Inc.).

The high falling velocity of the Boomerang core allows coring in relatively precise locations. In conventional coring in deep water the ship will often drift over 1 km (0.6 mile) during core lowering.

3.2.2 Procedures

The Benthos Boomerang corer comes with a detailed instruction manual. This section of this handbook gives a brief overview of the coring operation for planning.

Deploying free-fall corers is easy. The corers, assembled according to the manufacturer's instructions, are dropped over the side in the vertical position. Care must be taken to avoid sudden swings, which may cause the pilot weight to move up the barrel and release the glass floats. The average round-trip time is 15 min/1,000 m (4.6 min/1,000 ft) of depth.

Recovery is most easily accomplished at night when the flash unit can be seen for several kilometers. When the flash unit is sighted, the ship is brought alongside, and the spheres are recovered with a modified boat hook. Daytime recovery can only be made in calm seas at moderate depths, so that the ship will not have time to drift far off station. A ship must be ready to recover the unit as soon as it surfaces.

3.3 SHORT CORERS

3.3.1 Description

Short corers are defined as corers that take samples less than 3 meters (10 feet) long. Both gravity and some piston corers fall into this category. Gravity corers are used more often to take short cores because they give better quality samples than do piston corers; however, piston corers can take longer cores. The main advantages of gravity corers are their easy use, reliability, and inexpensive price. A disadvantage is that they can only take good quality cores to lengths of 1 to 2 meters (3 to 6 feet). A summary of short corer characteristics is presented in Figure 3-7.

The basic method of operation for gravity and piston corers is shown in Figure 3-8. The corers are lowered on a wire until they are a few meters above the bottom. Then, either a release mechanism allows the corer to free-fall to the bottom or the winch is free-wheeled to allow the corer to fall to the bottom.

Gravity corers are of two general classes: Phleger corers and Ewing corers.

Phleger corers are usually 38 mm (1.5 inches) in diameter, take samples 0.6 meter (24 inches) long, and weigh about 0.18 kN (40 pounds). They are often used as trip weights for larger gravity or piston corers.

<u>Characteristics</u>	<u>Value</u>
Corer Overall Length	
m	0.98 to 4.57 (usually 1.83)
ft	2.5 to 15 (usually 6)
Weight	
kN	0.18 to 4.45 (usually 0.89)
lb	40 to 1,000 (usually 200)
Sample Length	
m	0.3 to 3 (usually 1.2 to 1.8)
ft	1 to 10 (usually 4 to 6)
Sample Diameter	
mm	38 to 67 (usually 64)
in.	1.5 to 2.6 (usually 2.5)
Ship Requirements	Winch, A- or U-frame
Wire	Capable of supporting the corer and wire out with an acceptable factor of safety; from 3.2 mm to 12.7 mm (1/8 in. to 1/2 in.) depending on the size of the corer
Accessories	Extra liners, spare core catchers, spare core cutters, end caps, release
Price (1978)	From \$400 for the small corers up to \$2,600 for a piston corer capable of taking a 3 m (10 ft) long sample
Manufacturers	Alpine Geophysical Associates, Inc. Benthos, Inc. Hydro Products, Inc. InterOcean Systems, Inc. Kahl Scientific Instrument Corp.



Figure 3-7. Summary of short corer characteristics (courtesy of Benthos, Inc.)

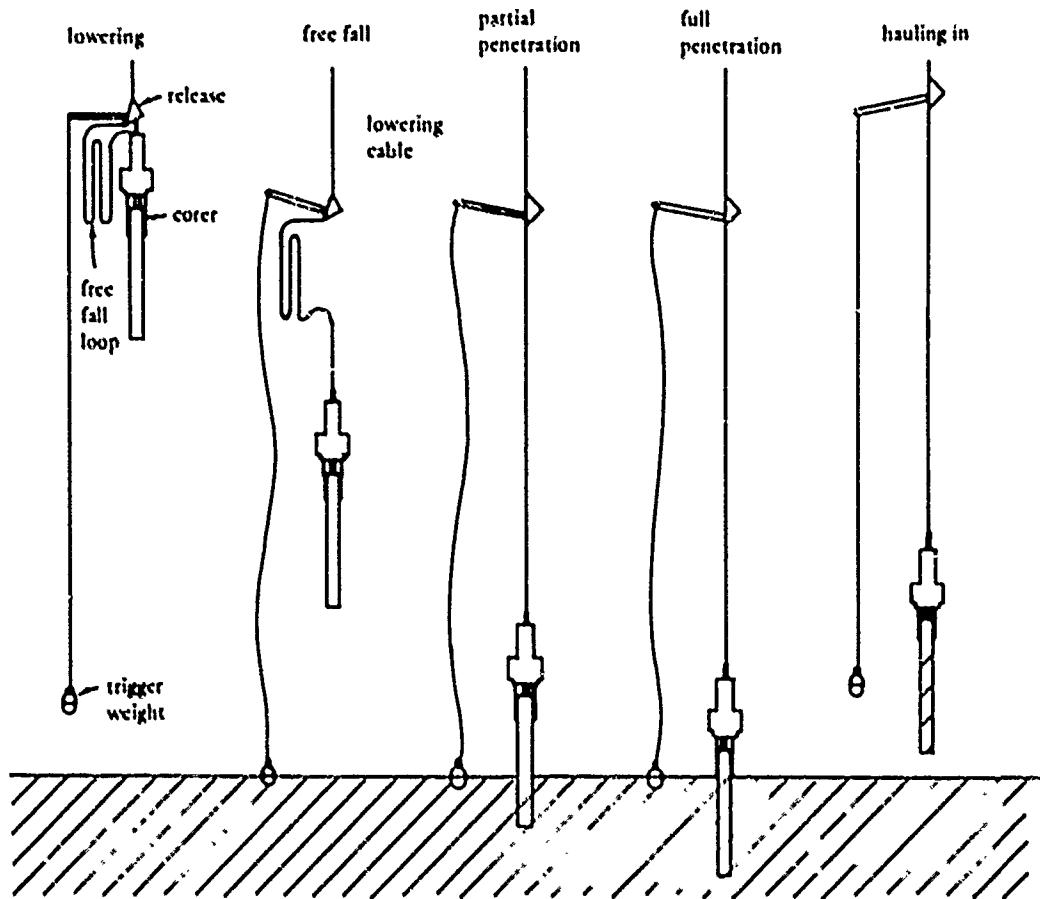


Figure 3-8. Principle of gravity corer operation (from Institute of Marine Resources Technical Report TR-38, 1972).

Larger gravity corers are often called Ewing corers. They usually take samples 64 mm (2.5 inches) in diameter, are 1.82 to 3.05 meters (6 to 10 feet) long, and weigh up to 1.1 kN (250 pounds). The weight of most Ewing-type corers can be varied by use of 0.22 kN (50 pound) lead weights.

Ewing corers are sometimes used as trip weights for long-piston corers because the piston core will not sample the first meter if the length of the free-fall loop or the trip wire is not exactly right. Using a gravity corer as a trip weight insures that a sample of the top meter of sediment will be recovered.

Figure 3-9 shows the parts of a short corer. This corer has a weight that drives the barrel into the bottom. A plastic liner is often used to keep the sample intact after removal from the barrel. A core cutter (nose cone) is used to reduce disturbance and retain the liner, and a core catcher prevents the sample from falling out. In gravity corers a check valve is often placed on the top of the corer to let water escape during penetration and to prevent water from washing out the sample during recovery.

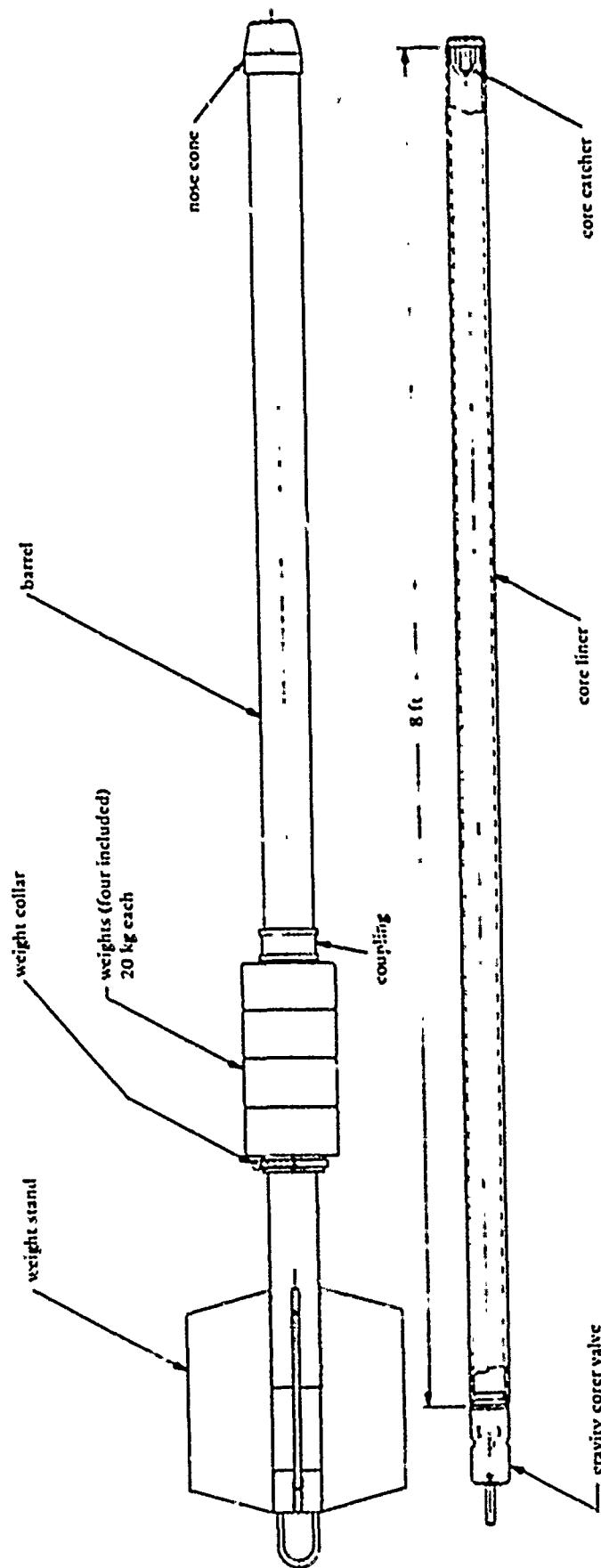


Figure 3-9. Typical gravity corer (courtesy of Benthos, Inc.).

Piston corers look like gravity corers, but the check valve is replaced with a piston attached to the lowering wire. The piston remains near the top of the sediment by sliding up the barrel as the corer penetrates the seafloor. Hydrostatic pressure helps to push the sediment into the barrel; consequently, piston corers take longer samples than do gravity corers.*

The quality of gravity cores is equal to or better than that of piston cores (Lee, 1973; Demars, 1975), but gravity corers are limited in subbottom depth by their inside diameter. Hvorslev (1949) found that the maximum length-to-diameter ratio for a nearly undisturbed sample in cohesive sediments on land is from 10 to 20. However this ratio does not apply directly to oceanographic corers and larger length-to-diameter ratios may yield adequate samples.

When trying to get longer gravity cores, a problem other than disturbance arises: selective sampling. As gravity corers penetrate, side friction between the sediment and the liner eventually causes a plug to form at the core cutter. If the soil is layered, the stiffer layers will be forced into the corer while some of the softer layers will be pushed aside. Designs based on the stronger soils will be seriously in error. These conditions may exist over about 10% of the seafloor. In areas where this type of layering occurs, a piston core is recommended.

3.3.2 Procedures

Short corers are easy to use because they are small and lightweight. Gravity corers are simple to assemble; piston corers are more complicated. Minimum maintenance is required to keep either type in good working order. Deploying and retrieving small corers usually goes smoothly. More detailed procedures for using short corers can be found in Dixon (1971) and in the "Instruction Manual for obtaining oceanographic data," published by Naval Hydrographic Office in 1968.

The corer is assembled according to the manufacturer's instructions. Special care should be taken to see that the check valve is working properly. If a trip arm release is being used, a safety pin should be put in before the corer is lifted off the deck. If the trip weight is lowered by hand, a safety line should be used. If a meter wheel or tensiometer is available and the seas are calm, no pinger is needed for depths under 2,500 meters (8,000 feet) (Dixon, 1971).

Gravity corers that will not be tripped should be lowered at speeds between 90 and 125 m/min (300 and 400 fpm). Gravity corers with a release mechanism should be lowered at 60 m/min (200 fpm). With nontripping corers, the winch should be stopped as soon as the corer hits bottom. With tripping corers, the winch should be slowed to 20 m/min when the corer approaches the bottom. After the core has been taken, the wire should be pulled in slowly until the corer is 100 meters (300 feet) off the bottom. After that, the corer can be retrieved at full speed until the corer approaches the surface. A man

*Piston corers are more completely discussed in the section on long-piston corers.

would be stationed on the fantail to indicate when the winch should be slowed down. Once the corer is brought on board, it should be kept vertical so the sediments do not mix. The order in which corer parts are removed will vary, depending on the type. It is important that the top cap be placed on the liner before the core catcher is removed. This will provide some suction to keep the core from sliding out of the liner. Section 5, Core Handling, describes what to do with the core once it is out of the barrel.

For maintenance the barrel and weights are washed down with freshwater, the threaded surfaces lubricated, and the check valve thoroughly cleaned and lubricated

3.4 LONG-PISTON CORERS

3.4.1 Description

Long corers are outfitted with pistons. Piston corers (Figure 3-10) offer the most practical method for getting detailed sub-bottom sediment strength information past depths greater than 3 meters (10 feet). A summary of long-piston corer characteristics is presented in Figure 3-11. Piston corers are capable of taking samples over 40 meters (130 feet) long (Driscoll and Hollister, 1974); however, the Navy's concern is with the top 15 meters (50 feet) (Clausner and Lee, 1975). Use of the piston in a corer allows long samples to be taken but has caused two problems: flow-in and piston surge. These are defined in later sections of this handbook.

3.4.1.1 Flow-In. The basic operating method is shown in Figure 3-12. The entire unit is

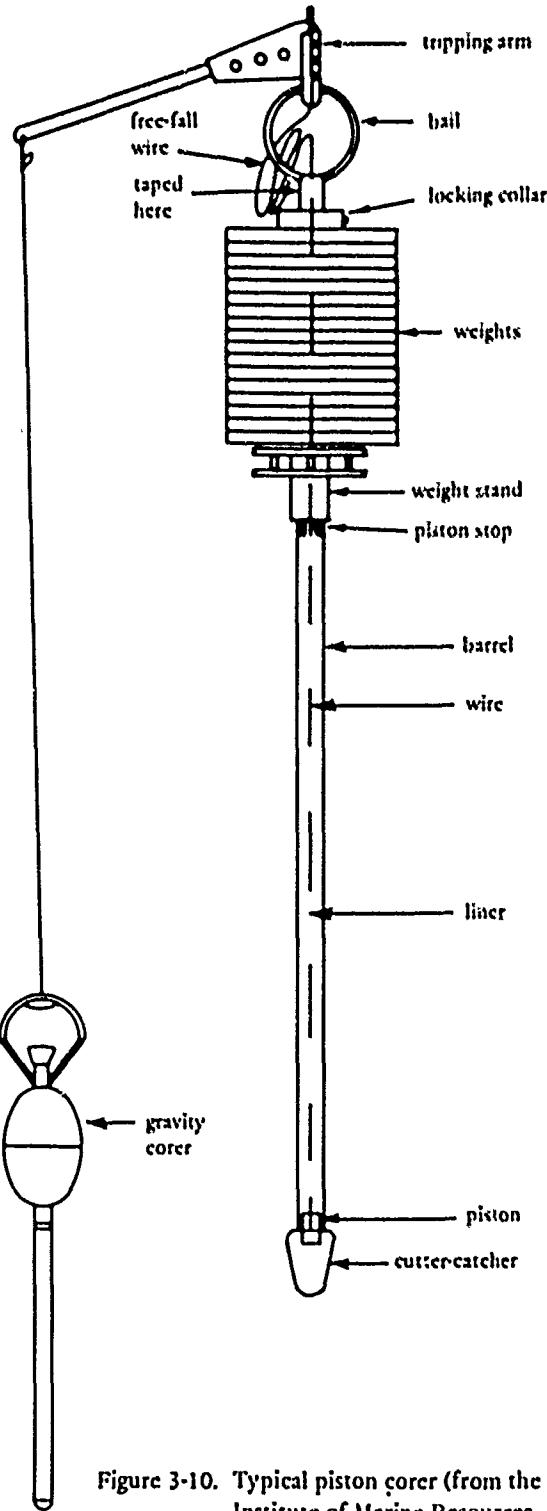
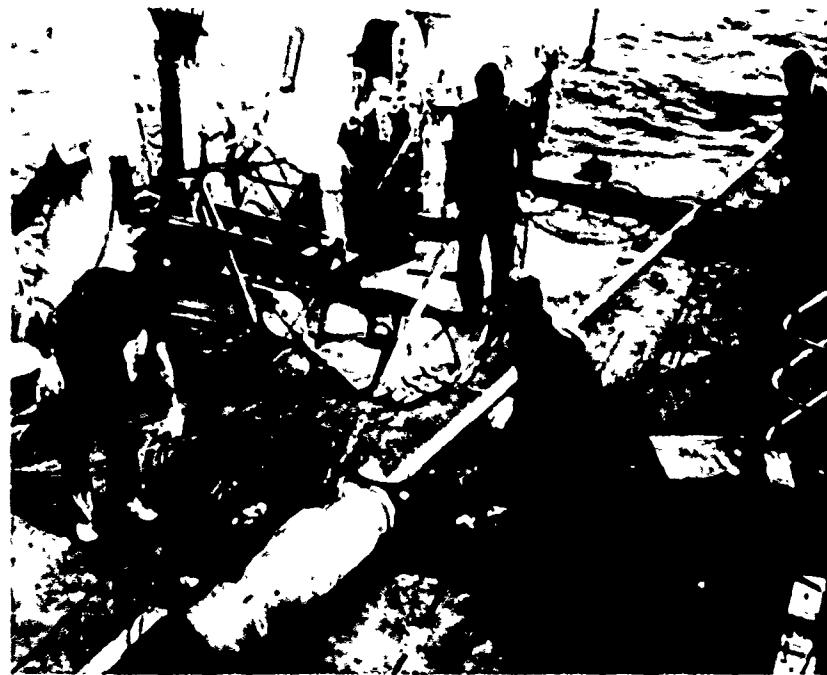


Figure 3-10. Typical piston corer (from the Institute of Marine Resources Technical Report TR-38, 1972).



<u>Characteristics</u>	<u>Value</u>
Corer Overall Length	
m	4.6 to 17.7
ft	15 to 58
Weight	
kN	1.1 to 11.1
lb	250 to 2,500
Sample Length	
m	1.8 to 15.2
ft	6 to 50
Sample Diameter	
mm	64 to 67
in.	2.5 to 2.64
Ship Requirements	Winch, A- or U-frame
Wire	Capable of supporting the corer and wire out with an acceptable factor of safety; from 4.8 mm to 14.3 mm (3/16 in. to 9/16 in.) depending on the size of the corer and water depth
Accessories	Extra liners, core catchers, core cutters, end caps, trip release
Price (1978)	From \$1,000 for the shorter corers to \$11,000 for the long corers
Manufacturers	Alpine Geophysical Associates, Inc. Benthos, Inc.

Figure 3-11. Summary of long-piston corer characteristics.

lowered on a wire from the ship. When the trip weight hits the bottom, the trip arm is free to pivot upwards, releasing the corer. A length of wire equal to the free-fall height is stretched taut when the corer just reaches the bottom. The core barrel penetrates into the seafloor while the piston remains near the sediment surface. The friction between the sample and the liner is so large that the sample would be shortened if the piston were not used. In piston corers this friction is overcome by hydrostatic pressure, which does not allow a vacuum to form between the piston and the sediment. The water pressure helps to push the sediment farther into the barrel.

While the piston aids in taking longer cores, it causes a problem during pullout. If the sediment does not completely fill the barrel the piston will be some distance below the piston stop. When tension is put on the line, the piston will be pulled up to the stop, sucking in more sediment. This extra sediment, called flow-in, is highly disturbed. The original sample is also probably slightly disturbed when the extra sediment is sucked in.

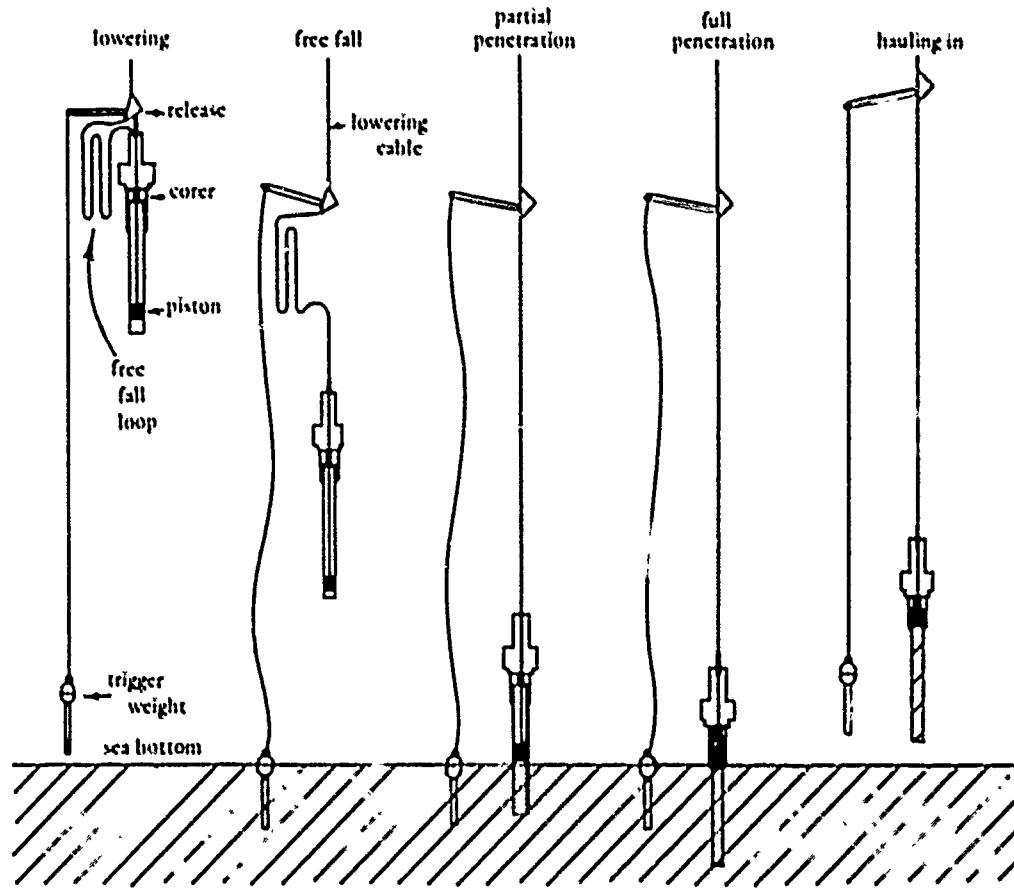


Figure 3-12. Principle of piston corer operations: Gravity corer used here as trigger weight (from Institute of Marine Resources Technical Report TR-38, 1972).

Experienced people can detect flow-in in layered sediment by looking at the cores after they have been split lengthwise, a common procedure for geologic analysis. Visual identification of flow-in in homogeneous sediments like pelagic clay is difficult. Splitting the core has a very big drawback, it makes a good strength measurement almost impossible. Vane shear tests on cores at standard diameters give low strengths (see Section 6.2). Therefore, cores should not be split when vane shear tests are to be run.

The solution to the flow-in problem is a split piston. In operation the lower piston section stays at the surface of the sediment while the upper section, attached to the main wire, slides up to the piston stop and lifts the corer out of the bottom. Both parts of the piston are held together by a shear pin that breaks when the free-fall wire is pulled taut and the corer penetrates the sediment; the sections remain hydraulically joined by an internal piston and cylinder. This hydraulic seal is in turn broken by seawater leaking into the cylinder through a hole in the piston. The size of this hole is important. If it is too small, the seal will not be broken in time, and the piston will act like a solid piston causing flow-in. If the hole is too large the piston will separate too soon, reducing core length. In spite of the danger of premature separation, a split piston should be used. Split pistons require careful maintenance to insure proper operation. The only commercially available split piston is sold by Benthos, Inc.; but CEL found this unit difficult to assemble. Lamont-Doherty Geological Observatory, however, has developed a split piston that works very well and is easy to assemble and maintain (Selwyn, 1978).

3.4.1.2 Piston Surge. The other major problem associated with piston coring is piston surge. For minimum amounts of disturbance the piston should remain motionless during the coring operation. The combination of ship motion and wire elasticity makes this impossible.

When a load is placed on a wire rope, it stretches. When the corer is tripped the wire suddenly contracts causing an elastic wave that travels up and down the wire. This elastic wave, called rebound, will shorten or lengthen the lowering wire. The amount of rebound depends on (1) the water depth, which determines how long it will take the elastic wave to travel back and forth, and (2) the free-fall height, which determines how long the corer will be free-falling and penetrating.

Besides causing piston surge, contraction and rebound cause another problem. As shown in Figure 3-13 (Driscoll, 1977), the pilot corer is often pulled completely out of the bottom and then penetrates. In very deep water the pilot corer may even be pulled out of the bottom a second time if the elastic wave is strong enough. Multiple penetrations like this make the pilot corer almost useless. A heavy pilot corer will cut down piston surge because it provides extra drag to the contracting cable.

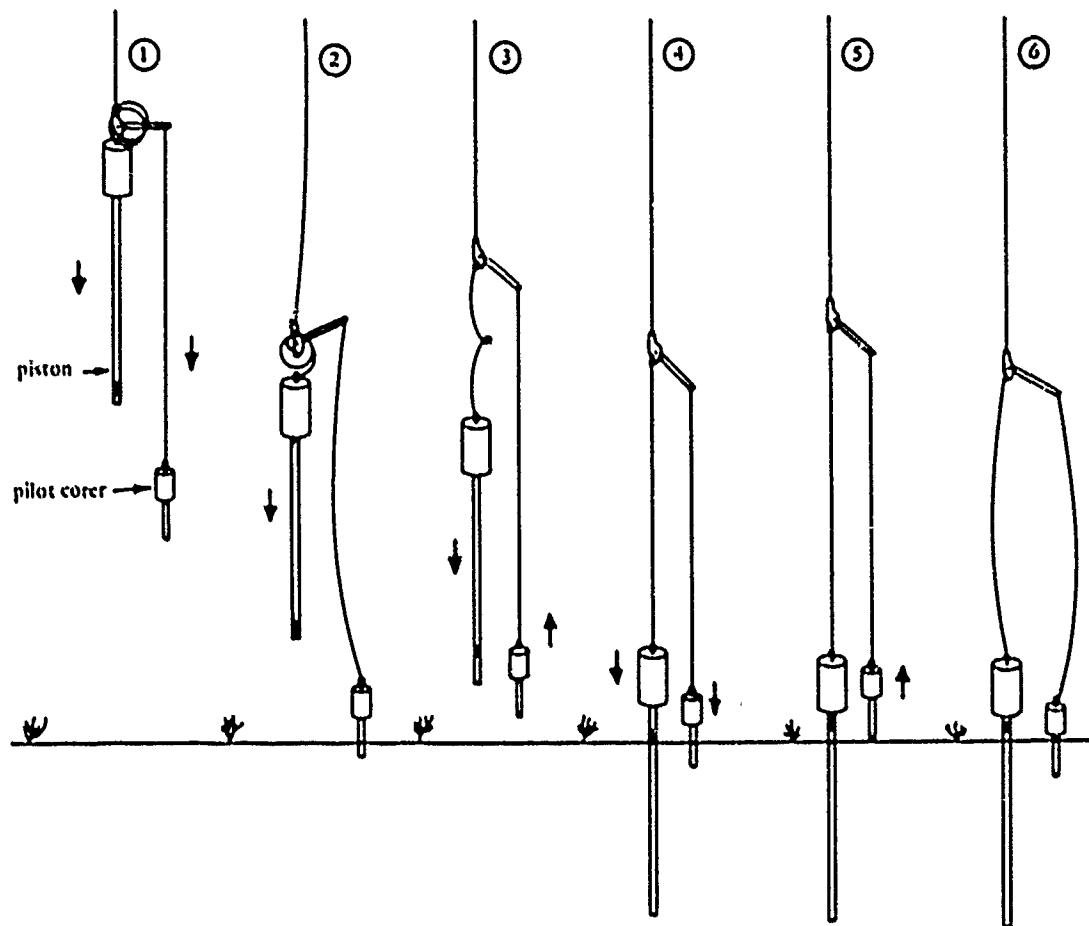


Figure 3-13. Effects of cable rebound on the pilot corer (from Driscoll, 1977).

Even when the contraction and rebound are considered, other factors influence piston surge. Ship motion transferred to the cable can cause piston motion on the order of 1 to 2 meters (3 to 6 feet). Also, as soon as the corer is released, the winch must be stopped so that extra cable is not payed out. This is a difficult task because of the time delay from the acoustic signal, the difficulty in seeing the change in load in deep water, and the inherent mechanical delays in the winch itself. If the winch is slowed before the corer reaches the bottom to prevent extra cable being payed out, the pilot corer will usually penetrate poorly or fall over.

With all these factors affecting the piston, it is not surprising that in deep water the first meter or two (3 to 7 feet) of a piston core are missing. No methods are universally accepted for reducing piston movement. At Scripps Institution of Oceanography, 0.6 to 1.5 meters (2 to 5 feet) are added to the free-fall loop, depending on lowering

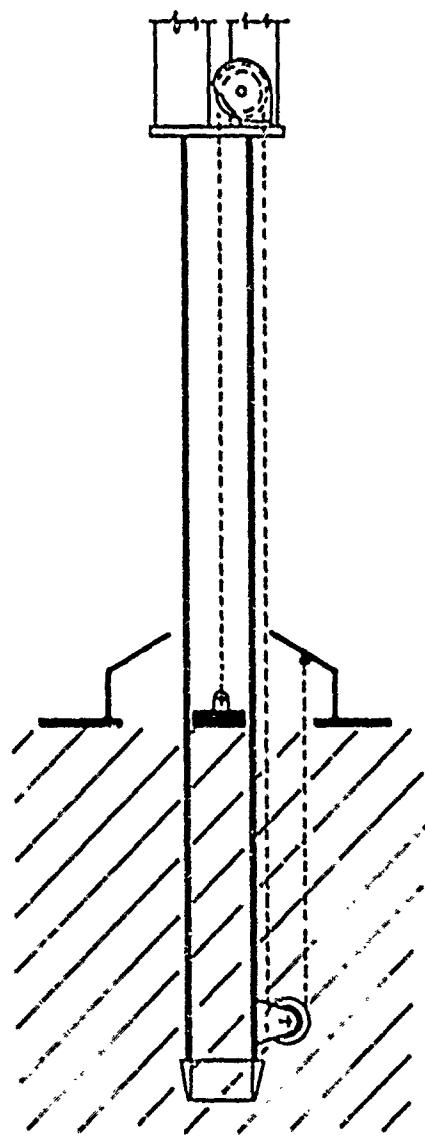


Figure 3-14. SACLANT recoilless piston corer.

rate and water depth (Dixon and Karig, 1969). In general, the extra wire payed out by the winch because of the time lag between tripping the corer and stopping the winch partially compensates for the contraction and rebound of the wire rope. With standard equipment this is probably as good an approach as any. If possible a box core should be taken at the same site as a piston core. Thus, the investigator is assured of getting a very good sample of the upper 0.6 meter (2 feet) of sediment.

Other solutions to the piston surge problem are possible, but all are fairly expensive. However, if the accuracy of the strength information is very important, the use of these solutions may be worthwhile.

(1) Hydraulic ram tensioners can be used to compensate for the ship's motion. Such units are considered expensive, but they could be adapted to many vessels without major modifications. They should eliminate a large portion of the dynamic motion transferred to the corer, reducing piston motion and greatly reducing the chances of pretripping.

(2) A small self-deployed gravity corer housed in the main corer weight is a possible solution to the multiply penetrating pilot corer problem (Driscoll, 1977). When the main corer is tripped, the gravity corer would also be released. Since it is isolated from the main wire, it would not be affected by rebound or contraction. Woods Hole Oceanographic Institution (WHOI) is presently working on the concept (Driscoll, 1977).

(3) Isolating the piston from the lowering line is the obvious solution to piston surge. The SACLANT ASW Research Centre* has developed a recoilless piston system (Kermaben and Cortis, 1968), that does this. The piston is attached to a bottom-resting platform by small cables and pulleys (see Figures 3-14 and 3-15). In water depths over

*Supreme Allied Commander, Atlantic, Anti-Submarine Warfare Centre, La Spezia, Italy.

1,500 meters (5,000 feet), the recoilless piston would reduce disturbance. Analysis of recoilless piston cores by CEL showed the bedding planes to be less disturbed; however, the strengths were only slightly higher than cores taken with the same corer using a conventional piston. The 1 sq m (39 sq in.) size of the bottom-resting platform makes handling the corer without a crane very difficult. For almost all operations the expense of making a platform and modifying a corer to accept it would not be justified.

As an alternative to the conventional lead and steel driving weights, CEL investigated the water mass corer (Niskin, 1975). Instead of weights, a large chamber is used to trap water. Long free-fall distances (15 meters, 50 feet) or more, are used to accelerate a large volume - 2.9 cu m (31 cu ft) - of water. Penetration was equal to that of cores taken when an equivalent mass of lead and steel was used. However, the large size of the corer head (Figure 3-16) made it difficult to handle without a crane. In cases where total weight is an important factor, these corers have an advantage: 7.2 kN (1,600 pounds) of water can be trapped in a head 0.6 meter (2 feet) in diameter, 2.4 meters (8 feet) long, weighing only 1.8 kN (400 pounds).

To insure 15 meters (50 feet) of penetration and still maintain an adequate safety factor of 2 in a typical wire rope 14.3 mm (9/16 inch) in diameter, a 13.3-kN (3,000-pound) weight limit (in air) should be placed on the corer. Also, the maximum outside diameter should not exceed 102 mm (4 inches) to keep breakout forces down to a safe level. Breakout forces can be estimated from the formula:

$$F_B = \frac{A_s S_u}{S_t}$$

where F_B = breakout force

A_s = side area of the core barrel

S_u = average undrained shear strength of the sediment

S_t = sensitivity of the sediment

When using long lengths of barrel, a barrel can be bent when the corer does not enter the sediment vertically and the length of the barrel exceeds penetration by a significant amount (McCoy et al., 1969). This is seldom a problem with barrel lengths under 9 meters (30 feet). However, if a number of 15-meter (50-foot) cores need to be taken, it is a good idea to bring along a few extra sections of core barrels.



Figure 3-15. SACLANT recoilless piston corer being deployed over the side of a ship.



Figure 3-16. Water mass corer during deployment.

Most of the major oceanographic institutions use some kind of pivoting stand to handle the core head. Also, the barrels must be rigged over the side because of deck space limitations and because of the stresses placed on long unsupported lengths of barrels when deployed over the stern. Also rigging over the side reduces the lifting requirements for A-frame or ship cranes. The maximum length of core that can be safely deployed over the stern is 10 meters (30 feet). Both WHOI and Scripps have plans available for pivoting head stands. These devices are recommended for use with the longer corers.

WHOI recently redesigned their standard piston corer (Driscoll, 1977). A major change is that most of the corer is made of stainless steel to reduce maintenance costs. Also, the weighted head has housings for a number of different instruments. Many other improvements allow easier and faster handling. If a design engineer is planning on buying a piston corer, the WHOI design is the best to be obtained.

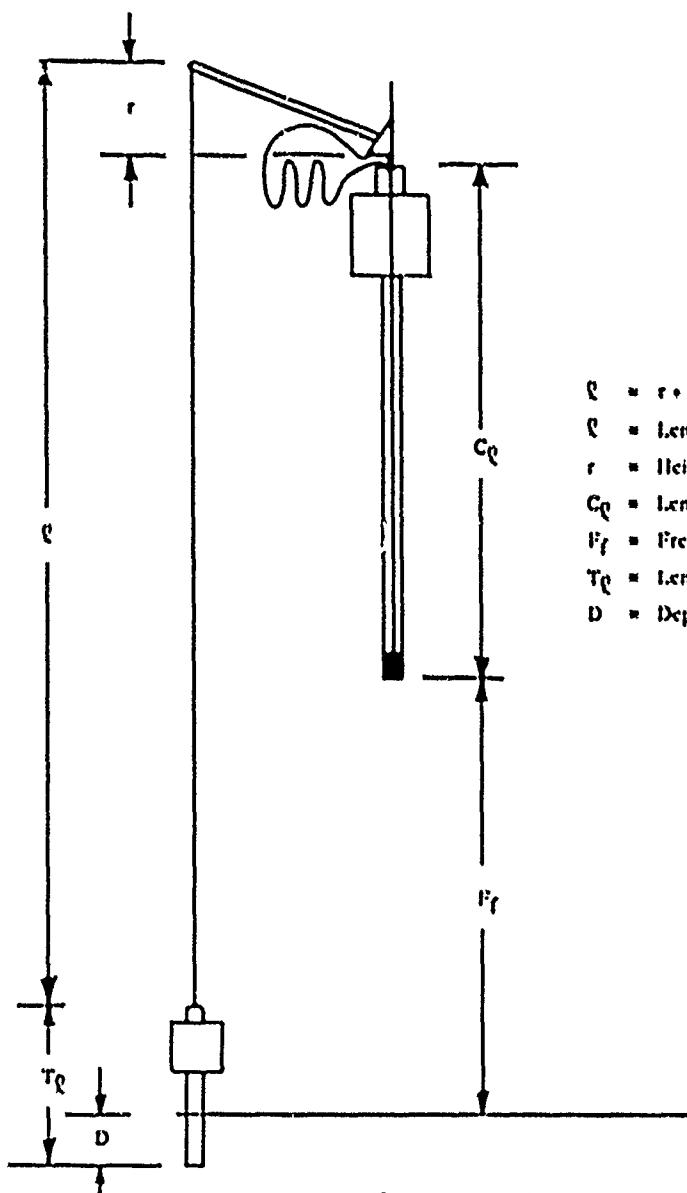
A discussion of a number of other pieces of equipment associated with piston coring can be found in Section 4.6, Associated Coring Equipment.

3.4.2 Procedures

Long-piston coring is a difficult and potentially dangerous shipboard operation. The difficulty increases as the length and weight of the corer and the state of the sea increase. The danger is associated with using heavy corers in deep water because the lowering wire is stressed to, and sometimes above, its safe limit. The basic steps in obtaining a core are assembly, deployment, and retrieval of the corer. Detailed instructions can be found in a Scripps handbook (Dixon and Karig, 1969) or a Naval Hydrographic Office (1968) manual.

The corer is assembled according to the manufacturer's instructions. The piston should be assembled with special care, particularly if it is a split piston. The most important part of assembly is calculating the lengths of the pilot weight and free-fall cables.

Figure 3-17 shows how to calculate the length of the tripping cable. In general, D is assumed to be 0.6 meter (2 feet); but, if the bottom is thought to be very soft, D should be increased to 0.9 (3) or 1.2 meters (4 feet). Free-fall heights of 3, 4.5, and 6 meters (10, 15, and 20 feet) are recommended for corers under 6, 9 to 12, and 15 meters (20, 30 to 40, and 50 feet) long, respectively. Wire contraction should be taken into account for light corers - under 4.4 kN (1,000 pounds) - when the water depth is greater than 3,000 meters (10,000 feet) and for heavy corers - over 8.9 kN (2,000 pounds) - when the water depth is greater than 1,500 meters (5,000 feet). This



ℓ = $r + C_Q + P_f - (T_Q - D)$
 ℓ = Length of trip cable
 r = Height trip arm must move to release coier
 C_Q = Length of the coier
 P_f = Free-fall height
 T_Q = Length of the trip coier or trip weight
 D = Depth of penetration of trip coier or trip weight

Figure 3-17. Calculation of trip cable length.

can be done either by adding length to the tripping wire or by letting the winch pay out extra wire. The equation for the amount of stretch in a wire rope is as follows:

$$S = \frac{W L \ell}{A E}$$

where S = amount of elastic stretch
 W = buoyant weight of the corer
 L_x = length of line out
 A = metallic cross-sectional area of the wire rope
 E = modulus of elasticity of the wire rope

Determining how much to add is based largely on experience. Scripps (Dixon and Karig, 1969) recommends adding from 0.6 to 1.5 meters (2 to 5 feet). The tripping wire length and free-fall height should be recorded along with other important information on a core log sheet, a sample of which is shown in Figure 3-18.

One person should direct corer deployment, which for long corers will involve coordinating the efforts of four to six persons. It is during this phase of the operation (and again during recovery) that the rotating head stand makes the operation much simpler and safer (see Figure 3-19). With this device free heavy lifts of lead and steel weights are avoided. Without a rotating head, coring is usually limited to sea state 3 or less. Also, a part of the deployment (often left out of instruction manuals but which should be performed) is the use of a hose to slowly fill the barrel with water as the barrel is being lowered into the ocean. By keeping the water level equal, hydrostatic pressure will not force the piston up the barrel or out the nose.

The two principal methods for deploying piston corers - off the fantail and from the side - are shown in Figures 3-20 and 3-21. Cores up to 9 meters (30 feet) long can be deployed from the fantail on many large oceanographic research vessels. Larger corers require a capstan to hold back the head as the barrels rotate over the stern of the ship. When deploying a corer that is mounted on the rail, the barrel is lowered by a capstan with a wire fairleaded through a small davit (Figure 3-22).

With either method, once the corer is vertical, the tripping weight should be lowered and attached to the tripping arm (Figure 3-22). The corer is then lowered, and a pinger is attached to the line 40 or 92 meters (100 or 300 feet) above the corer. Maximum lowering rates for a piston corer are usually 55 to 60 m/min (180 to 200 fpm).

The method used to compensate for wire contraction determines the lowering rate of the corer when the bottom is neared. If the wire contraction is taken into account in the free-fall loop, the winch should be slowed to 10 m/min (30 fpm) when it approaches the bottom and then stopped the instant the corer is released. Unfortunately, the length of the pilot corer is reduced.

A second method of wire contraction compensation is to allow the corer to hit at full lowering speed. The winch is then run 2 to 4 additional seconds before it is stopped. Part or all of the contraction is compensated for by the extra wire payed out by the winch. A longer trigger core results.

CORE LOG

Cruise Title _____ Date _____

Ship _____ DEPTH _____

Latitude _____ Original _____

Longitude _____ Correction _____

Bathymetry _____ Corrected _____

TYPE OF SAMPLE TIME

Piston _____ Start down _____ local _____ z

Trip gravity _____ On bottom _____ local _____ z

Gravity _____ On deck _____ local _____ z

CORER DETAILS

Length of barrel _____ Lowering rate _____

Free-fall height _____ Pullout load _____

Trip wire length _____

Sample Description (Type and Conditions) _____

Length of Sample and Penetration of Corer _____

<p



Figure 3-19. Rotating corer head stand for simplified over-the-side deployment.

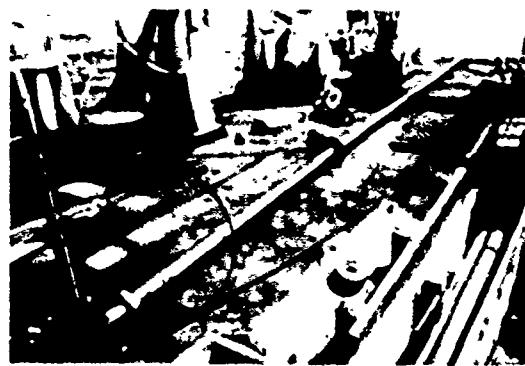


Figure 3-20. Corer being rigged for over-the-fantail deployment.



Figure 3-21. Corer rigged for over-the-side deployment.

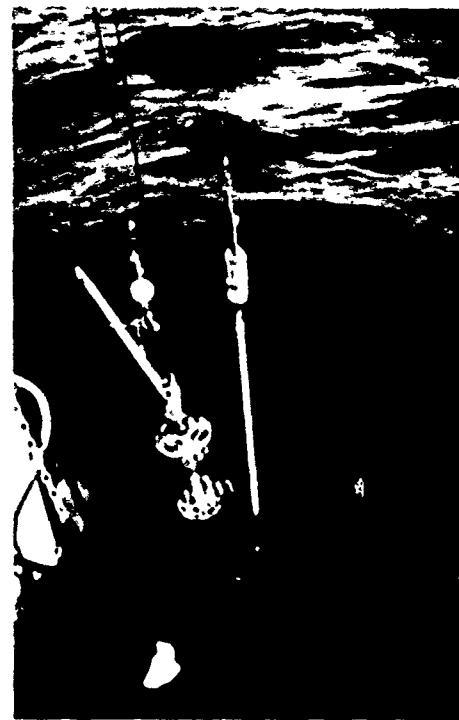


Figure 3-22. Tripping weight (small gravity corer) being lowered for attachment to tripping arm.

The corer should be left in the bottom for 1 minute to allow the piston to separate. Then the wire should be hauled in very slowly until the corer has cleared the bottom. The corer can then be retrieved at full speed until it approaches the surface whereupon the speed should be reduced. A person should be stationed on the fantail to watch for the pinger, which should be removed when it surfaces.

The release will surface next. A capstan is often necessary to haul in the pilot corer. When the pilot corer comes onboard, it should be handled according to the method described in Section 3.3.2. Getting the piston corer back onboard is the reverse of deploying it. Care should be exercised to minimize core disturbance; e.g., the corer should not be allowed to hit against the side of the ship. Once the liners are removed, the suggestions in Section 5 on handling the core should be followed.

A good piston core has 0.3 to 0.6 meter (1 to 2 feet) of water between the top of the sediment and the bottom of the piston. If there is a greater distance between the sediment and piston, the free-fall loop is too short and should be lengthened by an amount equal to the excess distance. If the mud marks outside the corer show significantly greater penetration than core taken, then the free-fall loop is too long and should be shortened by the difference between penetration and core length.

Piston corer maintenance is necessary to prevent corrosion. If the time between uses is greater than 24 hours, the barrels should be hosed down with freshwater and grease applied to sliding surfaces. For long-term storage, grease should be applied to the inside of the barrels to prevent rusting. Split pistons should be completely disassembled, inspected, and lubricated after each use.

3.5 ASSOCIATED CORING EQUIPMENT

With the exception of free-fall corers, successful coring requires several other pieces of equipment; probably the most important of these are the wire and its termination. Other equipment include winches, liner materials, pingers, releases, and core catchers.

3.5.1 Wire Rope

The most common wire rope used for coring operations is of 3x19, manufactured by United States Steel (USS) and designated as Monitor AA grade, torque-balanced, wire rope. This type of rope resists rotation at high loads, a very desirable characteristic for coring; is usually galvanized for resistance to corrosion; and also has a very high strength-to-weight ratio, a necessary characteristic for deep ocean work. Standard sizes for operations with large corers are 12.7 and 14.3 mm (1/2 and 9/16 inch). Many oceanographic vessels carry wires for use with smaller corers; 4.8 and 6.4 mm (3/16 and 1/4 inch) are the common sizes. A complete listing of the sizes and characteristics for this type of rope is presented in Table 3-1. Weight of the rope in water is 86.9% of the weight in air. Young's modulus for this rope is 1.45×10^5 kPa (21×10^6 psi).

The major concern with wire ropes is their maximum safe load; a good rule is to keep a safety factor of at least 2 (Walsh, 1978) against the breaking strength. The static load is very easy to calculate; it is the total of the buoyant weights of the wire out and the piece of equip-

ment. Dynamic effects are not easy to calculate and can add large forces to the static force. CEL has developed a number of computer programs (Liu, 1971) that predict these dynamic forces. A significant problem occurs when the wire rope goes into resonance. In this case, snap loads can occur when the dynamic forces exceed the static forces; the corer actually becomes weightless for a short time before the load is reapplied over a very short time span. Snap loads put very high stresses on the rope and on the termination.

Table 3-1. Galvanized 3x19, Torque-Balanced, Monitor AA Steel Wire Rope^a

Rope Diameter (in.)	Breaking Strength (lb)	Approximate Elastic Limit (lb)	Yield Strength (lb)	Weight/Foot (lb)	Area (sq in.)
11/64	3,500	2,620	3,100	0.0507	0.01394
3/16	4,000	3,000	3,500	0.0586	0.01611
7/32	5,400	4,050	4,750	0.0795	0.02184
1/4	6,750	5,050	5,900	0.0997	0.02738
5/16	10,300	7,700	9,100	0.153	0.04206
3/8	14,800	11,100	13,000	0.22	0.06015
7/16	20,000	15,000	17,600	0.304	0.08330
1/2	25,700	19,200	22,600	0.398	0.10919
9/16	32,500	24,400	28,600	0.492	0.13491
5/8	40,300	30,200	35,500	0.602	0.16515
3/4	57,800	43,300	50,900	0.879	0.24116
7/8	78,000	58,500	68,600	1.21	0.33202
1	100,600	75,400	88,500	1.56	0.42833
1-1/8	124,000	93,000	109,000	1.96	0.53737

^aTaken from United States Steel (1974).

CEL also has a computer program (CABANA) that predicts the stresses due to snap loads (Liu, 1973). CEL ran program CABANA, using the characteristics of a typical long-piston corer deployed off the stern of a Navy AGOR in a sea state 3. The program predicted resonance at a depth of about 5,800 meters (19,000 feet) and a 50% probability of reaching a dynamic load of 21.8 kN (4,900 pounds), a 10% probability of reaching a dynamic load of 25.8 kN (5,800 pounds), and a 1% probability of reaching a dynamic load of 30.2 kN (6,800 pounds). In general, smaller wire ropes, because of their increased flexibility, have larger dynamic loads that occur at shallower depths.

Another problem with wire ropes is their bending stress. This occurs when the rope is bent over a sheave, drum, or roller. For 3x19 wire rope, the minimum ratio of sheave diameter to rope diameter is 42. For example, the minimum diameter sheave that should be used with a 14.3-mm (9/16-inch) diameter wire rope is 0.6 meter (24 inches).

3.5.2 Terminations

Terminations are fittings that attach to the end of a rope that allow the rope to be attached to a piece of equipment. Equipment losses are often due to termination failure. There are two classes of terminations, permanent and temporary. Temporary terminations are also called field-applied or reusable fittings. Permanent fittings are not always used in oceanographic operations for three reasons:

- (1) One termination configuration may not be compatible with all the pieces of equipment.
- (2) Permanent terminations often will not fit through sheaves and holes in the deck during rerigging.
- (3) Permanent fittings often require special tools and trained personnel to apply them.

Fittings used in piston coring have to fit through the piston stop and are therefore limited in size. For most corers, the termination has to be 50.8 mm (2 inches) or less in diameter to fit through the corer head. One termination made that meets this constraint and is compatible with the pistons is an Electroline product made by Superior Switchboard & Devices. This fitting, called an eye-socket assembly or siege fitting, has a number of good features; it can be quickly applied without special tools, is reusable, and develops the full strength of the rope.

When a piston core is not needed, a hard eye and clips are often used as a termination. Clips are easy to put on, require no special tools, are reusable, and develop 75% to 80% of the strength of the rope (Myers, et al., 1969). Terminations for smaller wires - 6.4 mm (1/4 inch) or less in diameter - can often be swaged onboard ship.

A pull test is recommended for terminations when they are first put on. It is a good idea to test to the maximum expected load. After the test the termination should be retightened if possible. The termination should be checked frequently - as often as each use for critical pieces of equipment.

3.5.3 Winches

Winches should not be taken for granted for oceanographic operation because they can seldom operate at full capacity in these circumstances. The condition of the winches should be checked before an operation, particularly when working with heavy loads or in deep water. Most research vessels have two or more winches. One is usually a hydrographic winch, and the other is a deep sea winch or trawling winch.

Hydrographic winches are small; typically they have up to 9,100 meters (30,000 feet) of 4.8-mm (3/16-inch) wire rope. They can pull 8.9 kN (2,000 pounds) at 61 m/min (200 fpm). Deep sea winches on oceanographic research vessels often have from 9,100 to 13,700 meters (30,000 to 45,000 feet) of 12.3-mm or 14.2-mm (1/2- or 9/16-inch) wire rope. When new, these winches can pull from 146.8 kN at 41 m/min to 30.2 kN at 183 m/min (33,000 pounds at 133 fpm to 6,800 pounds at 600 fpm). Most deep sea winches consist of a storage drum and a traction unit that pulls the wire rope. Other types are single unit winches that store the wire rope under tension, which will eventually damage or crush the wire rope.

3.5.4 Liners

Most core liners are made of cellulose acetate butyrate (CAB) tubing because it is inexpensive and clear. However, CAB presents two problems in this use: first, it is not very strong and can rupture during piston coring; and second, CAB has a rather high rate of moisture loss, 0.1009 gm/sq cm per day (Appell, 1965). The best transparent plastic liner material is rigid polycarbonate, which is available, is much stronger than CAB, loses 0.0082 gm/sq cm moisture per day (13 times less than CAB), and is only slightly more expensive than CAB.

Polyvinyl chloride (PVC) has good mechanical properties and moisture-loss characteristics. However, it is opaque and contains heavy metals which can cause problems in chemical analyses.

Ideally, core liners should be one continuous piece to prevent leakage and damage to the piston seals. However, it is not practical to transport long liners or store them on shipboard. Also, it may be difficult to assemble the corer with the long liners. For easiest shipment and assembly, liners in 3-meter (10-foot) pieces are acceptable. A thin stainless steel tube can be used to help strengthen the joints.

3.5.5 Pingers

Pingers are useful in coring operations for two reasons: first, they show how far off the bottom the corer is, and second, they can give better definition of subbottom layers than the ship-mounted acoustic profiler. Once the water depth is over a few hundred meters a pinger is necessary to get the exact distance to the bottom. With piston corers this information is especially important because the winch will have to be stopped as soon as the corer is triggered. In an area with rugged topography, a line-mounted pinger can find a good location to take a core that the ship-mounted PDR would have trouble locating because of side reflections.

The pinger used should be a 12-kHz bottom-finding pinger, capable of operating to the depth of the area of interest. The output should be a minimum of +93 db referenced to 0.1 Pa at 0.914 meter (+93 db referenced to 1 μ b at 1 yard). The repetition rate should be once a second. Pulse lengths should be in the range of 0.5 to 10 ms.

Pinger batteries are either rechargeable or replaceable. Rechargeable pingers with an external charging plug are preferred and eliminate the need for opening the pressure housing. Some people favor pingers with replaceable batteries because these pingers do not have a charging penetrator that may fail. At CEL it is believed that it is more likely that an O-ring may be damaged during battery replacement than that a penetrator would fail.

3.5.6 Releases

The release mechanism is a critical part of coring. Pretripping results in a great deal of lost time or in the loss of the corer if the termination fails. As shown in Figure 3-23, a release is basically a lever arm with a wire clamp attached. When the trigger weight hits the bottom, the weight is taken off the tripping arm allowing the arm to pivot upwards and release the corer bail. The corer then free falls to the seafloor.

Pretripping is caused when dynamic motion of the ship is transferred through the lowering wire to the corer. If the movement is violent enough, the associated velocity and acceleration effects may overcome the mechanical advantage of the trip arm, releasing the corer prematurely. The corer then free falls until it is arrested by the termination on the lowering line. The free fall for a long-piston corer can be over 20 meters (66 feet). The impact of the corer against the termination puts a great deal of force on the termination, which sometimes fails, resulting in loss of the corer.

Pretripping can be prevented in a number of ways. First, the tripping arm can be made longer, increasing the safety factor against pretripping (Figure 3-24). Often the arm will have to be strengthened to withstand the extra bending moment, but this leads to other difficulties. The arm may become so heavy that its weight alone may prevent the corer from releasing, particularly if the corer is light. Also, the heavier arm will make the release more difficult to handle. These difficulties can be avoided by making the tripping arm out of high strength steel. Another way to prevent pretripping is to make the trigger weight heavier. This also increases the stresses and requires that the tripping arm be strengthened.

The University of Hawaii (Woodruff, 1969) developed a trip release with a messenger-activated safety device (Figure 3-25). In rough seas the safety lever prevents pretripping until the messenger hits the striker plate. A drawback to this system is the delay involved while the messenger slides down the cable, which could result in the ship's drifting off-station.

A popular method of preventing pretripping is use of a pressure-activated safety pin. The Pressure Powered Release, as shown in Figure 3-26, is manufactured exclusively by Benthos Inc.; it consists of a stainless steel housing and a piston. At the end of the piston is an O-ring seal which confines a small chamber at atmospheric pressure.

The piston is restrained by pins calibrated to shear at precise depths as the piston is forced in by external pressure. The pin fits on the body of the release and the end of the piston rests in a hole in the tripping arm. The arm cannot move up to release the corer until the piston is forced in. The Pressure-Powered Release has some drawbacks. The release is calibrated for regularly spaced depths only up to 1,970 meters (6,500 feet), and the maximum calibrated depth is 3,400 meters (11,200 feet) (Benthos, 1971). To make the device usable in deeper water it must be calibrated for various combinations of shear pins. Using the brass pins supplied, CEL found the maximum depth of activation to be 5,436 meters (17,800 feet).

Based on CEL's experience with releases, the following release characteristics are recommended. A static safety factor of 3:1 against pretripping should be used. This safety factor should depend on a heavy trip weight, preferably a gravity corer. By concentration of most of the safety factor in the trip weight, the release will be lighter (and thus easier to handle) and more versatile. The weight of the arm will not prevent smaller corers from tripping, and rebound will be reduced. Pressure-powered pins are recommended when using safety factors <3:1, and when corer-cable resonance is anticipated.

3.5.7 Core Catchers

Core catchers are traditionally mechanical fingers.. They are inexpensive and work on most kinds of sediment, but cohesionless sediment sometimes washes out. A number of other types of core catchers are available; the best is probably the sphincter type, in which the sphincter is a nylon sleeve attached to two rings. When one ring rotates 180 degrees, the nylon closes on itself. The SACLANT sphincter corer utilizes this type of core catcher; however, the ring rotation is activated by a somewhat complicated system consisting of a line that runs along the outside of the barrel to a sliding bar attached to the main lowering line. Kahl Scientific has developed a self-activated sphincter core catcher, which, if rugged enough, should be better than the mechanical finger type.

3.5.8 Sources of Equipment

Much of the time it is not practical to buy or fabricate the equipment needed for an operation; the alternatives are borrowing or renting the equipment.

The sources of coring equipment in the Navy are the Naval Oceanographic Office (NAVOCEANO), the Naval Facilities Engineering Command (NAVFAC), and CEL. NAVOCEANO in the past few years has had a reduction in staff; consequently, the amount of equipment they have provided has also been reduced. The only coring equipment NAVOCEANO can supply is a hydroplastic corer: a lightweight, 1.33 kN (300 pound) corer that can be used either as a gravity or piston corer.

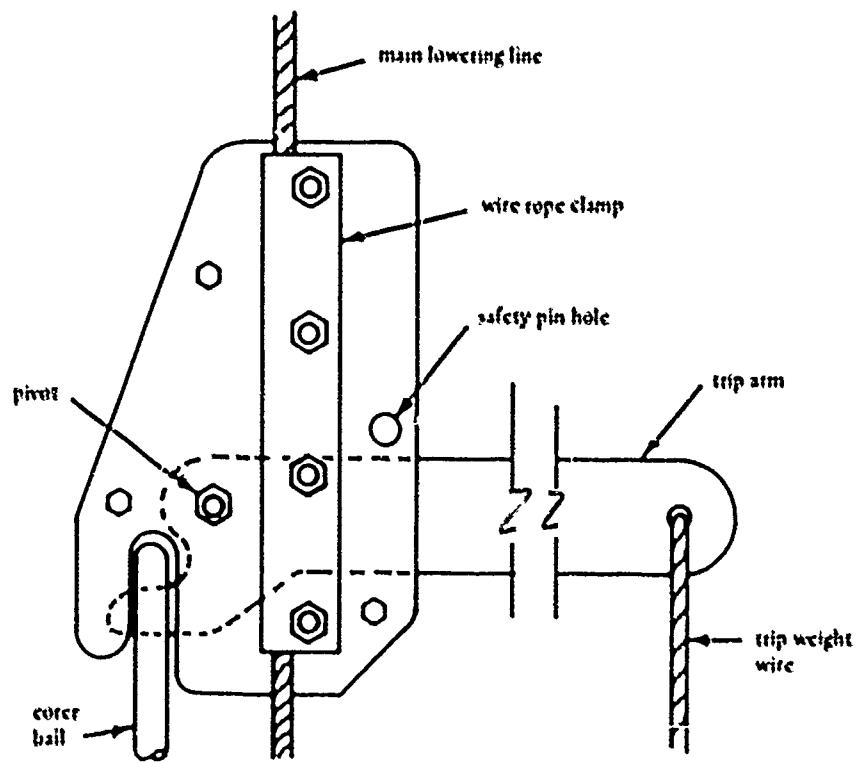
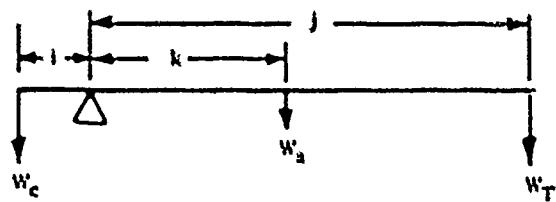


Figure 3-23. Typical trip-arm release.



$$\text{Safety Factor Against Pretripping} = \frac{j(W_T) + k(W_a)}{l(W_c)}$$

- l = Distance from pivot to coiled spring
- j = Distance from pivot to trigger weight
- k = Distance from pivot to center of gravity of trip arm
- W_c = Weight of coiled spring
- W_a = Weight of arm
- W_T = Weight of trigger weight

Figure 3-24. Calculation of safety factor against pretripping.

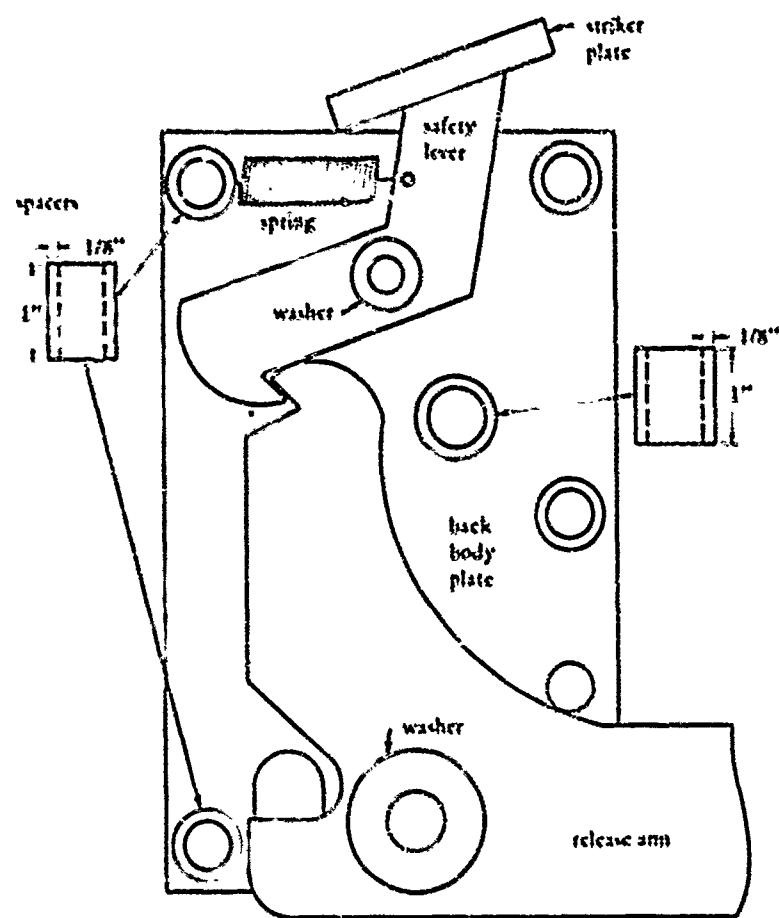


Figure 3-25. Internal view of the University of Hawaii release mechanism (by permission of Woodruff, undated).

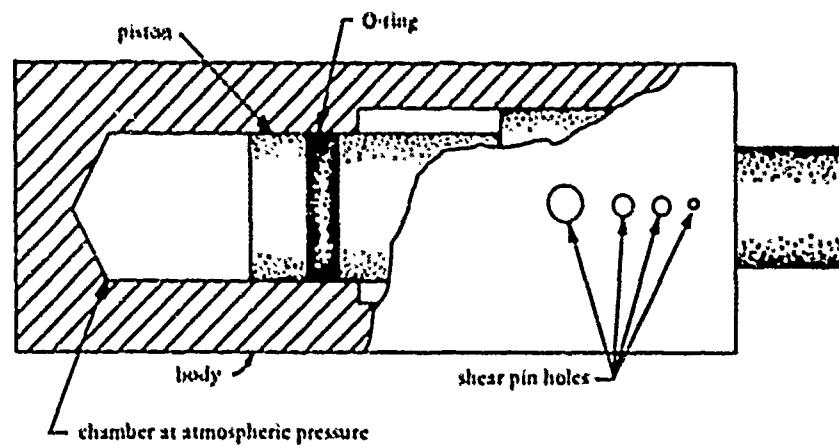


Figure 3-26. Benthos pressure-powered release (modified drawing from Benthos, Inc., 1971).

The Ocean Engineering and Construction Office of NAVFAC has in its equipment pool a 9-meter (30-foot) piston corer, a 2-meter (7-foot) gravity corer, Boomerang corers, various dredges, and 6,000 meters (20,000 feet) of 12.7-mm (1/2-inch) 3x19 wire rope. This equipment is available for use by Naval organizations on a cost-reimbursable basis.

CEL has a 12-meter (40-foot) sphincter piston corer, a 6-meter (20-foot) Ewing piston corer, a 12-klhz pinger, and a box corer. This equipment is also available for use on a cost-reimbursable basis.

Some colleges and universities have coring equipment that can be borrowed or rented.

Commercially, not much rental coring equipment is available. In contrast, many companies rent winches and wire. A good source of information is the current issue of Sea Technology as Buyers Guide/Directory (Compass Publications, 1977). The only companies renting corers were Alpine Geophysical Associates and Intersca Research Corporation (both listed in Appendix B). Intersca Research Corporation also rents A-frames, winches, and wire. Based on early 1978 prices a long-piston corer, A-frame, and winch with 6,700 meters (22,000 feet) of 6.3-mm (1/4-inch) wire rope can be rented for 30 days for \$2,600 plus shipping. Although a number of companies rent winches and wire rope, it is very difficult to find long lengths of large-diameter, oceanographic wire rope.

4. SURVEY PLATFORMS

This section discusses ships that can be used in taking sediment cores. As mentioned in Section 2.2, most ships associated with oceanographic research have the necessary equipment (PDR, sound source, and hydrophone) to conduct acoustic profiling. It is likely that a ship selected through the procedures that follow will be capable of conducting acoustic profiling.

Before searching for a usable ship the required ship characteristics must be determined based on the type of corer to be used. Oceanographic research vessels can be almost any size; however, most are from 15 to 91 meters (50 to 300 feet) long. From the coring standpoint, oceanographic vessels can be divided into two classes: vessels capable of taking long-piston cores at any site and vessels with less coring capabilities.

Vessels capable of taking 15-meter (50-foot) cores at most sites and water depths usually have one or two movable U- or A-frames and one or two deep sea winches with 6,100 to 12,200 meters (20,000 to 40,000 feet) of 12-mm (1/2-inch) or larger wire rope. Typically, they are at least 51 meters (200 feet) long, with a cruising range of 18,000 km (10,000 nautical miles). Many of these ships are Auxiliary Oceanographic Research Ships (AGOR) built for the Navy. The Navy controls four of these ships, but the majority are on permanent loan to universities and research institutions.

To be useful for limited coring operations in addition to free-fall coring, a vessel must have 4.8-mm (3/16-inch) or larger wire rope on a winch capable of pulling a minimum of 500 pounds. In general, the less capable vessels have 1,000 or 2,000 meters (3,000 to 6,000 feet) of 3/16-inch wire rope, a winch capable of retrieving the wire with a corer weighing several hundred pounds, and an A- or U-frame for launching and retrieving the corer. These characteristics cannot be assumed for any particular vessel; they are presented here as guidelines for what can be expected.

Probably the best source of information on oceanographic research vessels is the annual "Oceanographic Ship Operating Schedules," published by the Oceanographer of the Navy and the University-National Oceanographic Laboratory System (UNOLS). This report gives the basic characteristics and operating schedules for virtually all of the government-associated oceanographic research vessels over 15 meters (50 feet) long in the United States. The 1978 edition includes the full schedule, point of contact, displacement, cruising speed, year built,

and scientific personnel capacity for 100 ships and the length, area of operation, and point of contact for another 50 ships. Unfortunately, information on winches, wire, and deck equipment is not included. A good source for this information is "Jane's Ocean Technology" and the "Sea Technology Buyers Guide/Directory" (Compass Publications, 1977). "Ocean Industry" magazine also provides an annual listing and description of oceanographic vessels and work boats.

Of the 150 or so oceanographic research ships in the United States, the Navy directly controls 10; only 3 are available for coring. Other federal agencies operate 30 ships, most of which are operated by the National Oceanic and Atmospheric Administration (NOAA). Nearly all of the remaining ships are part of UNOLS and are operated by colleges and universities.

4.1 NAVOCEANO SHIPS

The details on the three oceanographic research vessels (AGOR) available for coring are presented in Figure 4-1. These ships are scheduled 1 year in advance. However, openings from cancellations are common, and cooperative cruises are possible. Scheduling of the ships is done by the NAVOCEANO, Bay St. Louis, Miss. The ships are operated by the Military Sealift Command (MSC).

The only corer that NAVOCEANO can provide is the hydroplastic corer (a short corer such as those described in Figure 3-7). The crew aboard the Navy AGOR is usually familiar with coring; however, the user should supply a person familiar with the corer and a person capable of directing deck operations. All of the AGOR's have a large crane on board, but policy is not to use the cranes while at sea. At present, the AGOR's are supplied to Navy users at no charge to the user (as of FY78) except for crew overtime.

4.2 NAVAL RESEARCH LABORATORY SHIPS

The Naval Research Laboratory (NRL) operates the USNS HAYES, a full capacity AGOR with a catamaran hull. This ship is primarily for NRL use; however, cooperative work is possible if NRL takes the leading role. On rare occasions USNS HAYES is not continuously booked for the entire year. At those times, a user pays the full operating costs, \$9,000 to \$12,000/day.

4.3 NOAA SHIPS

NOAA has 24 research vessels: seven of them can be classified as full capacity ships; most of the rest are capable of some kind of coring. These ships are available for use by other government agencies, but

like most other ships the NOAA vessels are scheduled a year or two in advance, making it difficult to get on the schedule for short lead-time operations. If a capable NOAA ship is operating near an area of interest, it may be possible to have a core taken, especially if operations take less than a day. A small job can probably be set up over the phone followed by a proposal to the cognizant Chief of Operations. Larger operations require a more formal request, justifications, and longer lead times.

4.4 U.S. GEOLOGICAL SURVEY (USGS) SHIPS

On the west coast, USGS operates two full-capacity ships, the SEA SOUNDER and the S. P. LEE. These ships are fully utilized by USGS; however, cooperative efforts are possible. USGS does not have ships on the east coast.

4.5 UNOLS SHIPS

In 1977, 62 ships over 15 meters (50 feet) long were part of UNOLS. Most of these ships are available on (1) a cooperative, not-to-interfere basis or (2) a reimbursable basis. Most of the full capacity oceanographic research vessels are AGOR's built by the Navy. The number of larger ships, 61 meters (200 feet) and longer, on each coast is about equal; the majority of the smaller ships are on the east coast.

Table 4-1 lists typical operating costs for UNOLS ships of various sizes. Universities usually have their own corers and experienced people to operate them.

4.6 COMMERCIAL OCEANOGRAPHIC RESEARCH VESSELS

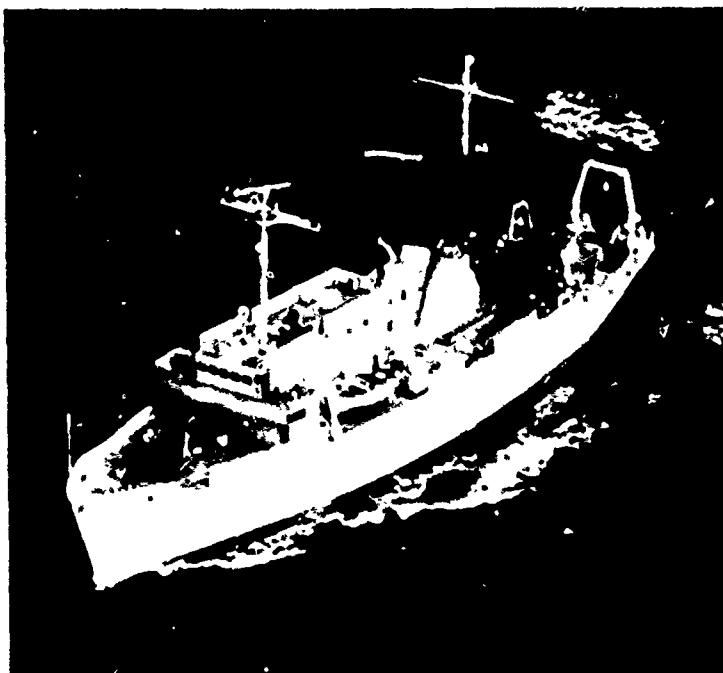
Commercial companies own very few true oceanographic research vessels. Some companies have ships that can be easily outfitted to do work in deep water. Many companies operate ships that can be outfitted to do work in shallow water, particularly when small corers are used. Some of the larger companies offer a complete coring service (ship, labor, and core analysis).

Table 4-1. Costs^a of UNOLS Oceanographic Research Vessels

Length, m (ft)	Cost, 1978 (\$/day)
15-30 (50-100)	\$100-2,500
30-46 (100-150)	2,500-3,500
46-61 (150-200)	3,500-6,000
61-76 (200-250)	6,000-9,000

^aThe costs are for exclusive use of the vessel, including fuel. On cooperative efforts the costs are generally split along the relative percentages of use.

Length
 63.6 m, 208.8 ft
Beam
 12.1 m, 39.5 ft
Draft
 5.8 m, 19 ft
Displacement
 1,341 metric tons, 1,320 tons
Cruising Speed
 18.5 kn/hr
 10 knots
Range
 22,200 km, 12,000 nautical miles
Endurance
 30 days
Complement
 Civilian Ship Officers - 9
 Civilian Crew - 17
 Scientists - 15



Winches and Wires

Deep Sea	Double drum storage and traction unit capable of pulling from 146.8 kN at 41 m/min (33,000 lb at 133 ft/min) to 30.2 kN at 183 m/min (6,800 lb at 600 ft/min); 13,700 m (45,000 ft) of 14 mm (9/16 in.) 3 x 19 wire rope; breaking strength 145 kN (32,500 lb)
Intermediate	Single drum storage with 6,100 m (20,000 ft) of 12.7 mm (1/2 in.) 3 x 19 wire rope; breaking strength 114 kN (25,600 lb)
Hydrographic	One winch with 9,100 m (30,000 ft) of 4.8 mm (3/16 in.) 3 x 19 wire rope, breaking strength 17.8 kN (4,000 lb); and one winch with 7,600 m (25,000 ft) of 6.4 mm (1/4 in.) single conductor electrical cable, breaking strength 26.2 kN (5,900 lb)

U-frames, Cranes, Davits.

Starboard U-frame	Can withstand 156 kN (35,000 lb) line pull and lift 26.7 kN (6,000 lb), clearance is 4.27 m (14 ft) overhead and 2.13 m (7 ft) between the uprights
Stern U-frame	Can withstand 222 kN (50,000 lb) line pull and lift 44.5 kN (10,000 lb), clearance is 4.88 m (16 ft) overhead and 3.66 m (12 ft) between the uprights
Crane	Hydraulically actuated, the crane has a rotation speed of 1.3 rpm and a capacity of 11.1 kN (2,500 lb) at 17.4 m (57 ft) outreach to 106 kN (24,000 lb) at 5.79 m (19 ft) outreach. This crane cannot be used when the ship is at sea.
Davit	A hydraulically actuated modified crescent davit is located on the starboard side of the Q1 level. It is capable of lifting 6.67 kN (1,500 lb).

Figure 4-1. AGOR characteristics.

Tracor Marine Inc., which does some oceanographic research for the Navy, has ships with experienced crews, but these ships do not have corers or long lengths of oceanographic wire. Some typical rates for Tracor's ships are: \$1,600 to \$1,700/day plus fuel for a 46-meter (150-foot) ship and \$3,000/day plus fuel for a 53-meter (175-foot) ship. Tracor primarily operates off the east and Gulf coasts, although a ship could be sent elsewhere for a large operation.

The ocean services division of Alpine Geophysical Associates, Inc. does both piston and vibracoring, primarily in the coastal zone. Alpine has available for rent both equipment and crews. Alpine has a 90-foot vessel, the RV ATLANTIC TWIN, available for coring operations on the east coast and the Gulf of Mexico.

In most commercial ports vessels are available for hire. The problem is finding one that can be modified for a reasonable cost to do a required job. Oil company work boats are the best alternative to oceanographic research vessels. They often have a winch with moderate wire lengths and sometimes have an A-frame that can be easily bolted or welded on. These ships are fine for nearshore shallow work but it is difficult to find (and expensive to buy) the long lengths of special wire necessary for working in deep water. Also, these ships have limited personnel accommodations. Larger, Coast Guard-inspected vessels have enough crew members to help do the work, but smaller, noninspected vessels usually do not have extra help available. The crews are experienced at handling loads at sea, but seldom have had experience coring. Typical costs for oil company work boats in Port Hueneme, Calif. are:

<u>Length, m (ft)</u>	<u>Cost, \$/Day</u>
43 (140)	\$1,400 + fuel
49 (160)	\$2,500 + fuel
61 (200)	\$3,800 + fuel

Fuel can be a major item when calculating the cost of a cruise. The fuel cost for a 61-meter (200-foot) long oil company work boat is about \$100/hr when cruising.

Often, companies (a number of large firms and some small ones) that analyze cores do not own ships and have to lease them. Some of the companies that do this kind of work are Woodward Clyde, McClelland Engineers, Dames and Moore, and National Soils. Sometimes these firms will lease the ship, crew, and equipment and send the samples to another laboratory to be analyzed. On large jobs this is acceptable because of work involved in managing a large operation. On small jobs, it is usually better for the user to arrange for the ship, crew, equipment, and sample testing. Firms can be found by looking at advertisements or the professional directory or professional services sections of magazines such as Ocean Industry, Civil Engineering, Sea Technology, and others.

5. CORE HANDLING

5.1 SECTIONING

5.1.1 Piston or Gravity Corers

When a core is brought back to a support vessel, it is important to prepare the samples for storage as rapidly as possible. If a core liner is used (as recommended for most soil mechanics work) the liner is pulled out the end of the barrel and cut in increments about 1.5 meters (5 feet) in length. The core liner sections must be labeled immediately after cutting to avoid later confusion. A grease pencil on a surface that has been wiped clean is probably adequate for this initial label. The label should contain the core number, the section number (numbering from the bottom with the first section pulled out marked as No. 1 results in fewer chances for a mistake) and an arrow pointing to the top of each section. A continuous grease line the full length of the liner will help maintain relative orientation of the corer sections. If possible the core liner should be cut with a rotary-type cutting tool* similar to those used to cut plastic pipe. After the liner is cut, the sediment contained within is cut with a fine piano wire. Many groups use a hack saw and miter box for cutting liner and sediment. This produces some core disturbance but is an acceptable method in many cases. Core sections are sealed with commercially available plastic caps taped on tightly with electrical tape, which should be stretchy and stick to itself well.** When putting on the plastic cap, a knife blade or similar instrument should be held along the side of the liner to allow air to escape. A wide selection of plastic caps is made by the Protective Closures Company. Five to ten wraps of continuously stretched tape should be applied. The sealed core ends should then be dipped in a wax that does not become brittle when cold.

The length of each core section should be measured and the depth-in-core increment range of each section calculated. A permanent label containing this information, the direction to the top of the core, original section number, and any other identifying information should be prepared and taped onto the liner in a watertight plastic envelope.

*The correct size may not be commercially available. Machine shops such as the one at the Scripps Institution of Oceanography can fabricate a core cutter to size.

**Scotch 33 is often used.

Enough information to define the section should also be engraved directly onto the plastic liner with a soldering iron, taking care not to burn a hole through the plastic. Figure 5-1 shows a typical core section that has been cut, sealed, and labeled.

5.1.2 Box Corers

The stainless steel boxes used with box corers are not watertight. A sample for engineering analysis should not be left in a box for more than a few hours or significant changes in water content will occur. One way of preserving box core samples is to take subsamples with plastic liners such as those used in piston coring. Large-diameter (70 mm or more) liners should be used if available. The bottom end of the liner is filed down to provide a taper, and a number of liners are pushed all the way to the bottom of the core with a rapid, smooth motion. If the liner is rigged with a piston (positioned at the sediment surface and connected through a line to a rigid support overhead), less core shortening and disturbance (Figure 5-2) will be experienced.

When all the liners have been pushed into the box, the sediment around the liners is removed by hand and saved in plastic bags for tests (grain size, Atterburg limits, grain density, etc.) that do not require unremolded samples. The subsample cores are sealed on the bottom, the top of the liner is cut flush with the sediment surface, and the top is sealed as described previously. Core subsamples are then labeled, also as described in the previous section.

5.2 CORE STORAGE

Unless the sediment samples are to be tested within 1 or 2 months, they should be cut into shorter than 1.5-meter (5-foot) lengths, perhaps to about 0.5-meter (2-foot) lengths. This reduces leakage under high hydrostatic head and sediment consolidation under its own weight.



Figure 5-1. Typical cut, sealed, and labeled core section.



Figure 5-2. Subsampling of a box core.

Core samples should be stored vertically if at all possible and cushioned to protect the cores from ship vibration. Samples stored horizontally tend to settle to one side; then when they are turned upright, material flows into the open space along one side. Vertical storage will probably require fabrication of a rack that prevents core movement.

Refrigeration of samples at $5^{\circ}\pm 2^{\circ}\text{C}$ is highly recommended for all samples and mandatory for terrigenous sediments that may contain gases and considerable organic matter. Freezing of samples must be avoided; it completely alters the sediments' engineering properties. Humidity control to near 100% relative humidity is highly desirable since all plastic liners are somewhat pervious to water. If a humidity control refrigerator is not available, samples can be stored vertically in a tank of seawater. If samples are to be stored underwater, it is important for them to be sealed as well as possible and for sediment to completely fill its liner. Samples have a tendency to absorb available water (through negative residual pore pressures), and swelling may occur. The salinity of the storage water should not vary greatly from that of natural seawater (e.g., through evaporation); otherwise, osmotic flow of water in or out of the samples may occur.

Testing of samples should always be conducted as soon as possible. With calcareous and siliceous oozes and terrigenous silts this is particularly important since they densify quickly under the unavoidable vibrations found shipboard. With these "difficult" sediments it is recommended that a vane shear test be run at sea within a few hours after the core is taken. This can be done by inserting the vane into the end of each core section. At each vane test location a water content sample of 50 to 100 grams (0.1 to 0.2 pound) should be taken and tightly sealed in a small plastic container. By following these procedures data on nearly undisturbed material will be obtained before the sediment densifies.

5.3 TRANSIT

On the ship, cores should be kept in a refrigerator box positioned to minimize disturbance. Cores should be stored vertically and well-braced to prevent their being thrown around during rough seas. Upon arrival in port it is generally necessary to arrange for the cores to be shipped to a testing laboratory. Air freight is recommended since it minimizes the time the cores are in the care of another party and also reduces vibrations and shocks that might disturb samples. Refrigeration during air shipment is not required unless the samples are gassy or contain considerable organic matter. Samples of clays may be shipped horizontally. If shipped vertically, cores should be very well-braced, and shipping crates should be marked as to which end must be kept up. Crates should, of course, be marked as fragile and packed as if they will be mistreated. The samples should be marked as "ocean sediment samples from below the tide line" (never "soil") to avoid problems with agricultural inspection.

If a large quantity of samples is involved or if the cruise termination port is distant, the samples may have to stay aboard until a continental United States port is reached. This should be avoided if possible. If necessary, however, ship personnel should be requested to check the samples and the refrigerator temperature daily and tighten the bracings for the cores as needed. If the refrigerator shows any tendency toward freezing it should be turned off. Samples stored without refrigeration are usable although somewhat degraded; frozen samples are not usable.

Upon arrival at a continental United States airport or port, the samples should be immediately transferred to a vehicle and transported to a testing laboratory. At the laboratory, samples should be stored vertically, refrigerated, and maintained at near 100% relative humidity or under water.

6. LABORATORY TESTING

6.1 RECOMMENDED TESTING PROGRAM

6.1.1 Required Engineering Properties

The objective of any sediment testing program for support of ocean facilities engineering is to furnish information on soil properties for analysis of the behavior of a proposed structure (anchor or foundation). At the present time, this analysis consists primarily of predicting limiting or failure conditions; that is, will an anchor actually pull out of the seafloor or will a foundation experience a bearing capacity failure?

Considerably more complex analyses are used on land to predict how far a structure will move when loaded, even though the load is well below failure. Elaborate constitutive relations for soil are needed and this requires very high quality samples and sophisticated tests. In the ocean, however, high quality samples can seldom be obtained (except with short box cores), and most structures can withstand relatively large movements and remain functional. It is generally required only that the structure not fail. An exception is a large downward bearing footing supporting movement-sensitive instruments. In this case compression as well as failure stress sediment parameters are needed.

In most seafloor facility analysis problems, therefore, the geotechnical engineer needs to provide good estimates of the strength of the sediment that is influenced by the facility over the length of time that the facility is used. For embedment anchors the strength should be known down to the subbottom depth that the anchor can penetrate

(perhaps 10 to 15 meters in soft sediments). For surface bearing foundations the strength needs to be known down to a depth of 1-1/2 to 2 times the width of the footing for insertion in standard bearing capacity prediction formulæ.

To account for time, geotechnical engineers generally consider two cases: (1) the end-of-construction, short-term (or undrained) case and (2) the long-term (or drained) case. The difference between the two is whether or not enough time is available to allow water flow into or out of the sediment pores. The tendency toward flow is produced by pore water pressures that are always generated when soil is loaded either in compression or in shear. In terms of real time, sands and clays are very different. In clays, undrained conditions may prevail to a large extent for days (or even for months) after the structure is loaded. Ultimately (perhaps after as much as a year or more), fully drained conditions will be established. In sand, drainage may occur within a few minutes, and the engineer need never consider the undrained strength.

For most loading situations in a clay or cohesive sediment, the undrained strength is lower than the drained strength. An exception is the long-term drained holding capacity of an anchor in a relatively stiff (overconsolidated) clay. For sands, loading conditions can always be considered drained.

For deflection-sensitive, downward-bearing foundations it will be necessary to predict settlements, particularly differential settlements. To make these predictions, certain consolidation parameters are needed: C_c , the compression index; c_v , the coefficient of consolidation; and C_s , the recompression or swell index. Of these, C_c is the most important since it leads to estimates of settlement on soft clay. The parameter C_s yields settlements on stiff clay, and c_v determines how long it will take for settlements to occur.

Table 1-2 lists the engineering properties needed to predict the ultimate capacity of most structures and the settlement of sensitive structures. The undrained shear strength, S_u , should be measured at

increments of about 0.3 meter (1 foot) over the specified subbottom depth range. The other properties should be determined for each clearly identifiable sedimentary unit.

6.1.2 Special Engineering Properties

Structures subjected to dynamic or repeated loads or designed to resist earthquakes may require additional properties. The research on which properties need to be measured and how to measure them is still continuing, so no firm recommendations will be made in this handbook. A simple rule for dynamic loading is that, generally, plastic clays and dense sands are not particularly susceptible to failure due to repeated loading. Coarser grained (foraminiferal) calcareous oozes are very highly susceptible, and silts and loose sands are highly susceptible to failure during repeated loading.

Stress-deformation (constitutive) relations may be desirable for some critical installation. High quality samples would be needed, and at this time no procedure exists for obtaining these samples from water depths deeper than about 500 meters (1,500 feet). Even in these cases, a drill ship or platform would need to be used in the sampling. Any work at this level would require the services of an experienced consulting engineering firm. These exact parameters would be needed if movements of only a few centimeters are intolerable.

6.1.3 Required Mass Physical Properties

Almost all performance prediction equations require the bulk sediment density (γ_t). Though this property can be measured directly by weighing a section of core and then measuring the volume it occupies (e.g., by sealing a section of liner and filling it with water), this direct procedure is relatively inaccurate and time-consuming. A faster and more accurate approach is to use the equation

$$\gamma_t = \frac{G \gamma_{sw}}{G w + \gamma_{sw}} (w + 1) \quad (6-1)$$

where G = grain density (weight/unit volume) (often called specific gravity)

γ_{sw} = density of seawater (about 1.025 g/cm³)

The grain density, G , can be measured directly (see Section 6.2.5) but can be estimated as 2.7 g/cu cm without significant loss in accuracy for most sediments (siliceous ooze excluded, grain density measurement required). The water content, w , is a simple property to measure (see Section 6.2.4).

Other properties are directly related to grain density and water content.

$$c = \frac{G w}{\gamma_{sw}} \quad (6-2)$$

$$n = \frac{c}{1 + c} \quad (6-3)$$

where c = void ratio

n = porosity

All of these relationships apply only to saturated sediments such as those usually found on the seafloor.

A parameter that is required in many performance prediction schemes is the effective overburden pressure or vertical effective stress, $\bar{\sigma}_v$, at the base of an embedded footing or the fluke of an embedment anchor. This quantity is obtained by multiplying the sub-bottom depth of interest, z , by the average submerged density of the sediment above z . Submerged density is defined as the bulk sediment density, γ_t , minus the density of seawater, γ_{sw} .

In summary, the only frequently required mass physical property is the sediment bulk density, which can be obtained most easily from the sediment water content.

6.1.4 Index Properties

Many other tests are often performed on marine sediments so that a classification can be assigned. These include:

1. Color
2. Atterberg limits
3. Grain size
4. Carbonate content
5. Organic carbon content

Except for nearshore terrigenous sediments that behave in a manner similar to that of soils on land, information on the listed properties is not directly useful for ocean construction. This is because correlations between index and engineering properties have not been developed for deep ocean sediments. If possible, however, it is recommended that index properties (with the possible exception of organic carbon content) be measured whenever engineering properties are determined. They can be used in correlating sedimentary units in adjacent cores, and they facilitate core description. Measurement of index properties also provides a service to the geotechnical engineering profession. If these properties are routinely measured and reported to an appropriate national data bank the development of a practical engineering classification system for deep ocean sediments will be possible someday.

For nearshore terrigenous sediments, the most valuable correlation is between the Atterberg limits parameter - plasticity index - and the ratio of undrained shear strength to consolidation (overburden) pressure, S_u/σ_v (Figure 6-1). This correlation applies only to normally consolidated cohesive sediments (i.e., those that have never experienced a greater overburden pressure than the one that exists presently - usually soft clay). Its use to estimate shear strength from

overburden pressure and plasticity index will yield a value lower than the true value for other sediments. The relationship is also conservatively in error for shallow subbottom depths (to 2 meters, 6 feet).

6.2 TEST PROCEDURES

6.2.1 Undrained Shear Strength

The undrained shear strength, S_u , of cohesive marine sediments has traditionally been measured by the laboratory vane shear test. This test is uniquely suited to very soft, shallow subbottom depth sediments that cannot stand under their own weight outside a core liner. As interest has grown in greater subbottom depth (>3 meters, 10 feet) and hence stronger materials, a greater emphasis has been placed on unconfined compression and triaxial shear testing. This has occurred since the materials can be trimmed and allowed to stand under their own weight and since additional information (primarily drained and dynamic strength parameters) can be gained. However, this added sophistication is unnecessary if the following criteria can be met.

1. Only S_u is required (not drained strength parameters).
2. Sediment has been sampled over the full subbottom depth range of interest.
3. The sediment is cohesive and plastic (little or no water rises to the surface when a pat of sediment is placed in the hand and the side of the hand is struck vigorously).

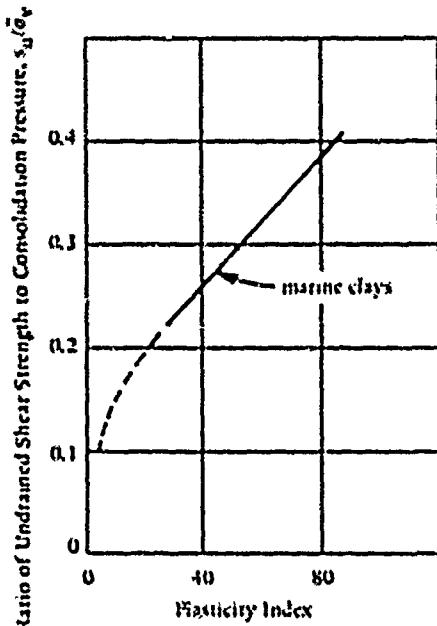


Figure 6-1. The S_u/σ_v ratio as a function of plasticity index (after Lambe & Whitman, 1969).

4. The core is of relatively good quality (internal structure and bedding planes are not totally distorted*).

When these criteria are met, the laboratory vane shear strength is adequate (with allowance for disturbance correction, discussed in Section 7) and no triaxial testing is needed. Otherwise, shear strength estimates should be based on triaxial tests. The unconfined compression test would be used only if vane shear testing equipment is not available.

All sediment cores are disturbed; their engineering properties are not the same as they would have been had the sediment remained in-situ. Disturbance almost always leads to a measured strength that is lower than the in-situ strength, perhaps by a factor of three or more. Two procedures, one involving vane shear testing and the other triaxial testing, are given in Section 7 for correcting strengths to their in-situ values. The procedure for vane shear strength corrections involves the measurement of a negative residual pore water pressure, u_r . A method for making this measurement is given in this section.

6.2.1.1 Vane Shear Strength. The laboratory vane shear test consists of inserting a four-bladed vane (Figure 6-2) into a sediment section and rotating the vane at a constant rate of rotation until a peak torque is reached. The vane shear strength is calculated as:

$$S_v = \frac{2 T}{\pi d^2 H \left(1 + \frac{d}{3 H} \right)} \quad (6-4)$$

where S_v = vane shear strength (assumed equal to the undrained shear strength, S_u , of the sample; not necessarily equal to the S_u^u in place)

T = peak torque

d = vane diameter

H = vane height

*Some upward bending of bedding planes near the core liner is unavoidable.



Figure 6-2. Vane shear device.

Vane shear strength is slightly dependent upon the ratio H/d and the rate of vane rotation. An H/d ratio of 2 is commonly used, although a value of 1 will not significantly affect results. Values <1 are unacceptable. A typical value for d is 1 inch (2.54 cm). Most laboratory vane tests have been conducted at a rotation rate of 6 deg/min. This rate is still recommended since it allows direct comparison with previous tests. Consideration has been given in the profession to standardizing the rate of vane shear testing at 90 deg/min. It

has been shown that this faster rate produces strength measurements about 10% to 15% higher than those from tests at the slower rate. If many tests are to be run in a short period of time (e.g., a profile down a split core) the rate of 90 deg/min is allowable, although the values should be reduced by about 15% to yield more standard results.

The vane should always be inserted so that the vane top is embedded by an amount at least equal to the vane height, H . The vane may be inserted in the end of a core section or a subsection with a length of at least $3H$.

Vane shear testing equipment is manufactured by Wykeham-Farrance Engineering Limited of Great Britain (distributed in the United States by Troxler Electronic Laboratories, Raleigh, N.C.). Torque is measured by a somewhat flexible calibrated spring. If possible, the spring should be replaced with a strain-gage-mounted torque cell. The spring cannot produce a constant rate of vane rotation.

Usually, two vane tests are made at each location in a core sample. The first or original strength is measured as described above. After this test is completed, the vane is rotated rapidly through one full

revolution. A second test is then conducted and yields the remolded strength. The ratio of original to remolded strengths is termed the sensitivity, S_t .

6.1.1.2 Negative Residual Pore Water Pressure. The residual pore water pressure is a measure of the level of disturbance that a core has experienced and forms the basis for one method of core disturbance correction (discussed in Section 7). This residual pressure exists in the water contained in sediment pores and is maintained by menisci at the sediment sample surface.

The residual pore pressure test is conducted with equipment that is not commercially available but that can be fabricated easily and economically. One needs a ceramic disc rated at 1 bar or more bubbling pressure (available through Soil Moisture Equipment Company, Goleta, Calif.). The disc diameter should be about 10 to 20 mm (0.25 to 0.5 inch) less than the ID of the core liner and about 6 mm (0.25 inch) thick. The disc is attached by epoxy to a slightly larger plastic disc fitted to a short section of pipe (Figure 6-3). The pipe is connected to (1) a pressure transducer that can measure negative pressures and (2) a valved tube for flushing and saturating the system.

The system is flushed with de-aired seawater and calibrated for various negative pressures: the full tube leading to the open flush valve is connected to a flask; the flask is placed at various heights below the disc; the disc is submerged in a small dish of water. The flush valve is then closed and the line disconnected. This device is placed on a freshly cut sample surface (end of core subsection) and must be suspended so that it exerts no weight on the sediment. Pressure transducer readings are made until a steady state value is reached (after about 10 min). This pressure is identified as the negative residual pore water pressure u_r .

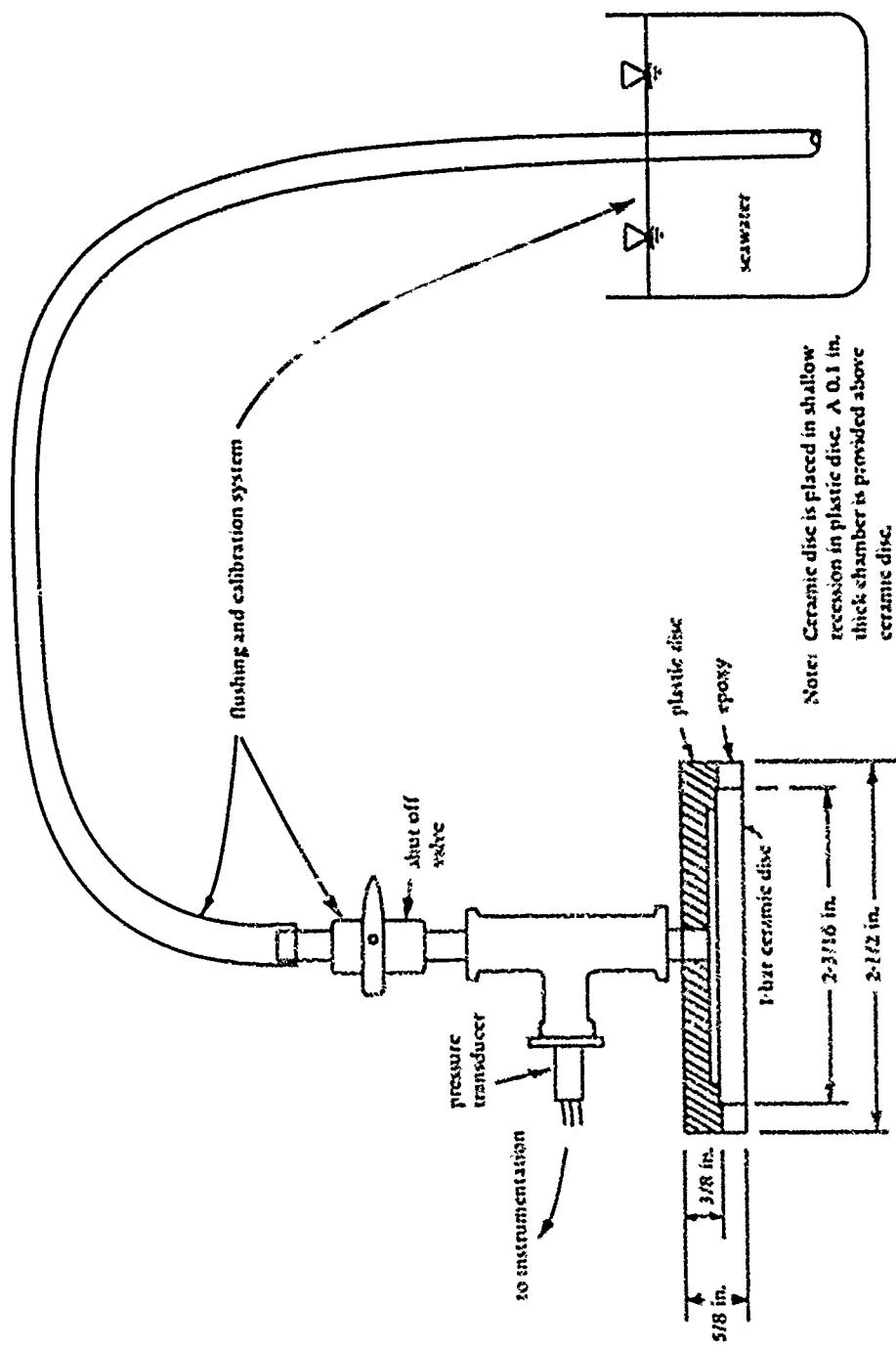


Figure 6-3. Residual pore water pressure measurement device.

6.2.1.3

Unconfined Compression Test And Unconsolidated-

Undrained Triaxial Test. In the unconfined compression test a cylindrical sediment sample - typically 89 mm (3.5 inches) high and 35.6 mm (1.4 inches) in diameter - is trimmed and placed in a device that allows it to be loaded axially at a constant rate of strain. The unconfined compression strength is defined as the peak axial load divided by a corrected cross sectional area:

$$A_c = \frac{A_o}{1 - \epsilon} \quad (6-5)$$

where A_c = corrected area

A_o = original cross-sectional area

ϵ = strain at failure

The undrained shear strength is equal to one-half the unconfined strength. If no peak load is reached, the strength is taken (somewhat arbitrarily) as that corresponding to 20% strain.* Trimming is done with a special trimmer available from several commercial soil-testing equipment firms and a wire saw (Figure 6-4). Loading devices are also available from several commercial firms. Testing should be conducted at a strain rate of about 2%/min. Detailed instructions for trimming samples and performing unconfined compression tests are given by Lambe (1951).

The unconfined compression test should only be performed on samples that do not slump under their own weight and that are

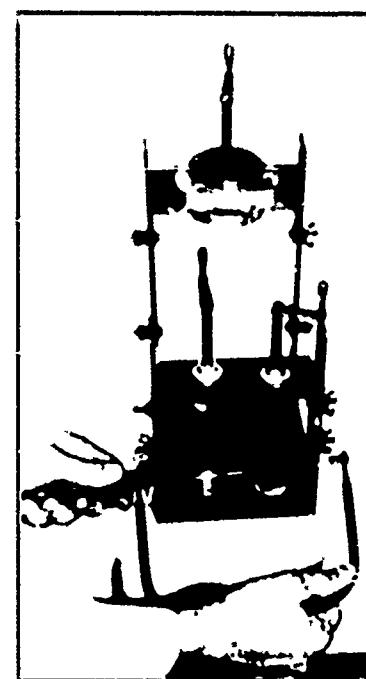


Figure 6-4. Trimming a triaxial test specimen (from Lambe, 1951).

*Strain is defined as change in length divided by original length.

cohesive and relatively impervious. Pelagic clays from subbottom depths beyond about 5 meters (15 feet) would usually meet these criteria; biogenous oozes and nearshore silty sediments generally would not.

The strength measured by the unconfined compression test may differ from the vane shear strength because of the difference in failure mode. The lower value would be used conservatively as the sample strength, which in turn may differ significantly from the in-place strength because of sampling disturbance.

The unconsolidated-undrained (UU) triaxial test provides information similar to that of the unconfined compression test. However, it can be used with somewhat softer and more pervious sediments, and it provides information that can lead toward the estimate of drained strength parameters. The UU test involves placing a trimmed cylindrical sample (same dimensions as given earlier) in a thin rubber membrane and sealing it with O-rings into a closed system with a pore pressure transducer. The system is backpressured in a triaxial cell and is loaded axially to failure as the pore water pressure changes are measured. Details of this procedure, including the analysis of pore water pressure development, are given in Section 6.2.2. For obtaining undrained shear strength, all that is needed is the failure load and strain. Strength is calculated as it was under unconfined compression testing.

The UU test would generally not be performed if only undrained shear strength were needed. However, if both drained and undrained properties are required, the test is valuable since it provides information toward both.

6.2.2 Drained Strength Parameters

6.2.2.1 Definitions of Terms. The principal drained strength parameters used for seafloor facilities engineering are the friction angle, ϕ , and the cohesion intercept, c . These are illustrated by a

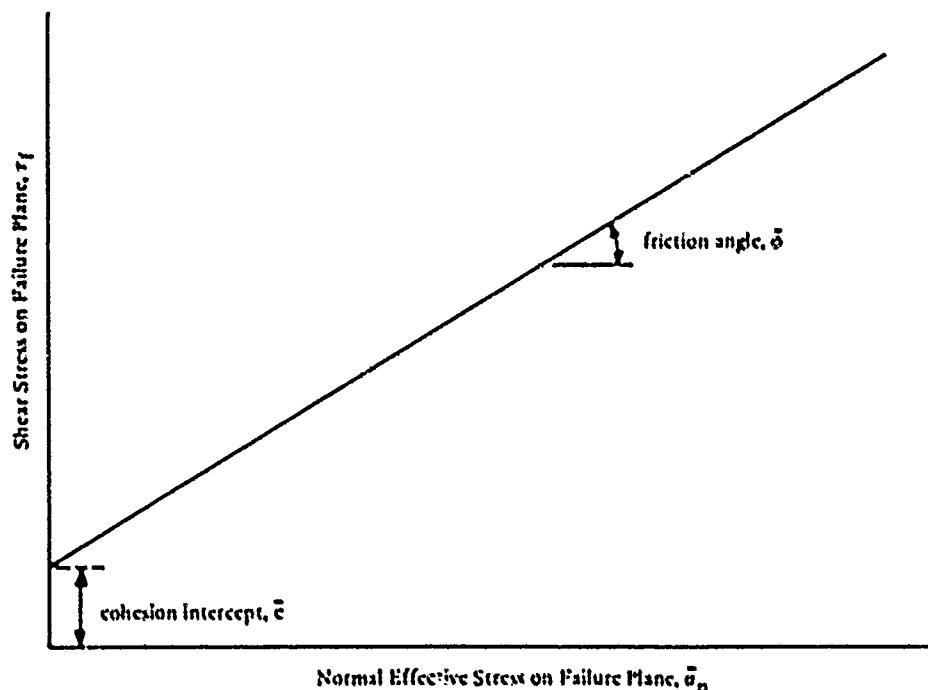


Figure 6-5. Definition of drained strength parameters.

plot of limiting shear stress (strength), τ_f , versus normal effective stress, $\bar{\sigma}_n$, on the plane of failure (Figure 6-5). These two terms simply define a failure envelope with the equation:

$$\tau_f = \bar{c} + \bar{\sigma}_n \tan \bar{\phi} \quad (6-6)$$

This is one of the classic soil mechanics equations, termed the Mohr-Coulomb failure criterion. It is a statement of the fact that soils are frictional materials that increase in strength as confining pressure increases. An important corollary to this is that strength of a uniform body of soil almost always increases with subbottom depth.

Another important concept which has broad implications is the effective stress principle. Effective stresses ($\bar{\sigma}$) are defined as the total normal stress, σ , minus the pore water pressure, u . The effective stress principle states that effective stresses control strength and compression behavior in soils. Therefore, as long as the terms of Figure 6-5 are defined in terms of effective stresses, it does not matter

whether test data are taken under drained, undrained, or even partially drained conditions. The limiting or failure stresses will still define the same failure envelope parameters, $\bar{\phi}$ and \bar{c} .

An important, commonly made error requires discussion. It is often stated that cohesive soils have a friction angle of 0 and a shear strength equal to the cohesion intercept, \bar{c} . Under short-term (undrained) loading conditions this is indeed the apparent situation. No matter how much the confining pressure is changed by loading, the undrained shear strength remains constant at S_u . However, as drainage occurs, the strength changes until finally the drained strength obeys the Mohr-Coulomb criterion with a substantial friction angle and only a small cohesion intercept. (The undrained strength obeys the criteria also if effective stresses are used.) The difficulty in using the $\bar{\phi} = 0$ assumption is that of the possibility of drained failure being ignored. This could be highly unconservative for certain situations. It is best to refer to the undrained shear strength as S_u and to use \bar{c} and $\bar{\phi}$ to define the drained or effective stress failure envelope parameters.

To obtain the parameters of Figure 6-5, several loading tests need to be run to failure, with continuous readings of normal stress, shear stress, and pore water pressure made during the tests. The envelope that separates loading conditions achieved during the test from conditions not achieved defines the terms \bar{c} and $\bar{\phi}$. One of the simpler ways to construct this envelope is through stress paths. A stress path is a continuous plot of a parameter, q , versus another parameter, \bar{p} . For a triaxial test (the only type to be considered here) q and \bar{p} are defined as:

$$q = \frac{\bar{\sigma}_v - \bar{\sigma}_h}{2} \quad (6-7)$$

$$\bar{p} = \frac{\bar{\sigma}_v + \bar{\sigma}_h}{2} \quad (6-8)$$

where $\bar{\sigma}_v$ = the vertical effective stress = (axial load/corrected area) - pore water pressure, u

$\bar{\sigma}_h$ = the horizontal effective stress = confining pressure - pore water pressure, u

Readings are made frequently, and \bar{p} and q are calculated for each of them. At least three tests on fresh, previously untested samples need to be run with each test starting at a different \bar{p} .* The stress paths will resemble those given in Figure 6-6.

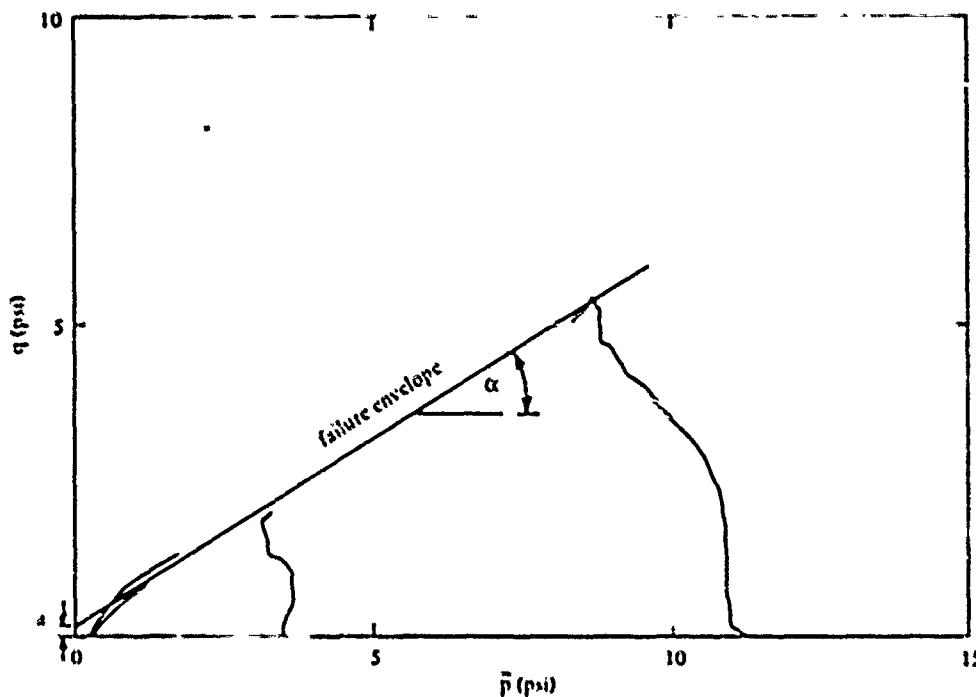


Figure 6-6. Four triaxial test stress paths with failure envelope.

A line that encloses the stress paths as well as possible is drawn, and its slope, α , and intercept, a , are determined. The parameters \bar{c} and $\bar{\phi}$ are obtained through:

$$\sin \bar{\phi} = \tan \alpha \quad (6-9)$$

$$\bar{c} = \frac{a}{\cos \bar{\phi}} \quad (6-10)$$

*Procedure for doing this is discussed later.

The stress paths may be such that only a broken-line failure envelope may fit them. In that case two or more sets of \bar{c} and $\bar{\phi}$ values may be obtained. The values that correspond to the appropriate stress level of the installed facility should be used.

The beginning \bar{p} 's (i.e., at $q = 0$) selected for constructing a figure like Figure 6-6 should bracket the range of stresses expected for the structure. At least one of the tests should be a UU (in Figure 6-6 the two small stress paths are from UU tests), and the others should have \bar{p} greater than three to five times the overburden pressure (see Section 6.1.3) from which the sample was taken. At CEL it has been common to run one UU test and two tests consolidated to 21 kPa (3 psi) and 69 kPa (10 psi), respectively. The samples should be as nearly identical prior to testing as possible. Box core samples are often ideal because they provide considerable material from the same subbottom depth.

In many design procedures it is recommended that both \bar{c} and $\tan \bar{\phi}$ be reduced to two-thirds of their original value if the soil is highly compressible or "loose." Most seafloor sediments would probably fit into this category.

6.2.2.2 Triaxial Testing. A triaxial test setup generally includes the following major components:

1. A water-filled cell that can be pressurized to apply a confining pressure to the sample.
2. A separate pressurizing system that leads to a membrane-enclosed sample within the pressure cell to allow backpressuring of the sample.
3. A means of loading the sample axially while it is in the pressure cell.
4. A means for measuring the load, displacement, confining pressure, and backpressure.
5. Valves that allow water to flow into or out of the sample and a volume change device that allows accurate measurement of the amount of water flow. This system is pressurized as indicated in item 2.

Figures 6-7 and 6-8 illustrate these major features. The entire system is usually "backpressured." That is, both the sample and cell are elevated to a pressure of about 350 kPa (50 psi) to guarantee saturation of the system. Small differential pressures between sample and cell are set up relative to the back-pressure. To properly saturate a sample, the backpressure should be applied for at least 24 hours prior to further testing.

A triaxial test typically has two distinct phases. In the first, a differential pressure is set up between the cell and sample so that the sample begins to lose water or consolidate. This differential or consolidation pressure, \bar{p}_c , is the initial point on a stress path such as those of Figure 6-6. This process of consolidation is continued until an approximate equilibrium is established in the sample; i.e., there is little tendency for additional water to flow. A way to recognize equilibrium is to plot the amount of water flow out of the sample versus \log_{10} (time since consolidation began). After the first minute or so, this plot should form a straight line that should continue from 10 minutes to several hours. At some point the line will break and reestablish itself again as a straight line with a much smaller slope. This break point marks the beginning of the establishment of equilibrium. To avoid a number of problems, consolidation should be conducted in several steps such as 3, 7, 14, 35, 70 kPa (0.5, 1, 2, 5, 10 psi) (size of pressure step increases with pressure level). Following the last consolidation step, a period of about 24 hours should be allowed to elapse before axial loading begins.

The second phase of a triaxial test involves failing the sample by loading it axially. This can be done in two ways. In the first, the valve leading to the sample is closed immediately prior to loading and the sample is sheared undrained: termed a consolidated-undrained

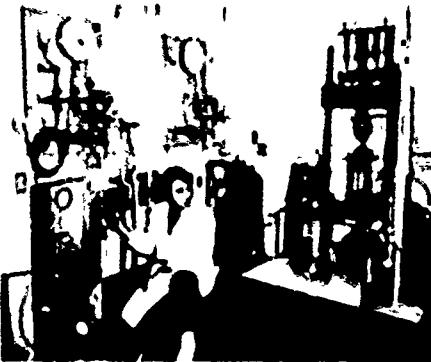


Figure 6-7. Complete set of triaxial test equipment.

(CIU) test. Pore water pressures developed during the load test are measured so that effective stresses can be calculated. In the second test type, the valve is left open and the sample is allowed to drain freely during shear: termed a consolidated-drained (CID) test. The CIU test is suitable for most applications since, through the effective stress principle, information on both drained and undrained behavior is obtained. An appropriate rate of strain during loading in a CIU test is 4%/hr. CID tests must be sheared more slowly. Tests should be continued to 20% strain. The CIU test is usually favored over the CID since it requires less time to perform and yields more information. The CID test would be used for research and for problems in which accurate estimates of deformations during drained shear are required.

A UU test is a special kind of CIU test. The sample is placed in the cell, and a reading is taken of its negative residual pore water pressure, u_r . This pressure differential, u_r , is then artificially set up between the sample and cell, and the sample is allowed to saturate for about 24 hours. The sample valve is then closed, and the sample is sheared as in a CIU test.

The previous discussion has included descriptions of several types of triaxial tests and the major steps involved in performing them. Numerous minor details have not been included; e.g., how to properly seal the sample, how to pressurize, types of load and pressure cells to use, etc. These would require a separate volume and are already adequately covered by the excellent text, Bishop and Henkel (1962). To have triaxial tests run on contract to a soils testing firm, the discussion included here should be adequate for preparation of specifications. To set up a triaxial testing facility, the reader should refer to Bishop and Henkel (1962) and consult with one of the major universities involved in triaxial work (e.g., Massachusetts Institute of Technology, University of California, Berkeley; Purdue University; University of Illinois; University of Washington), the Civil Engineering Laboratory, or the Army's Waterways Experiment Station.

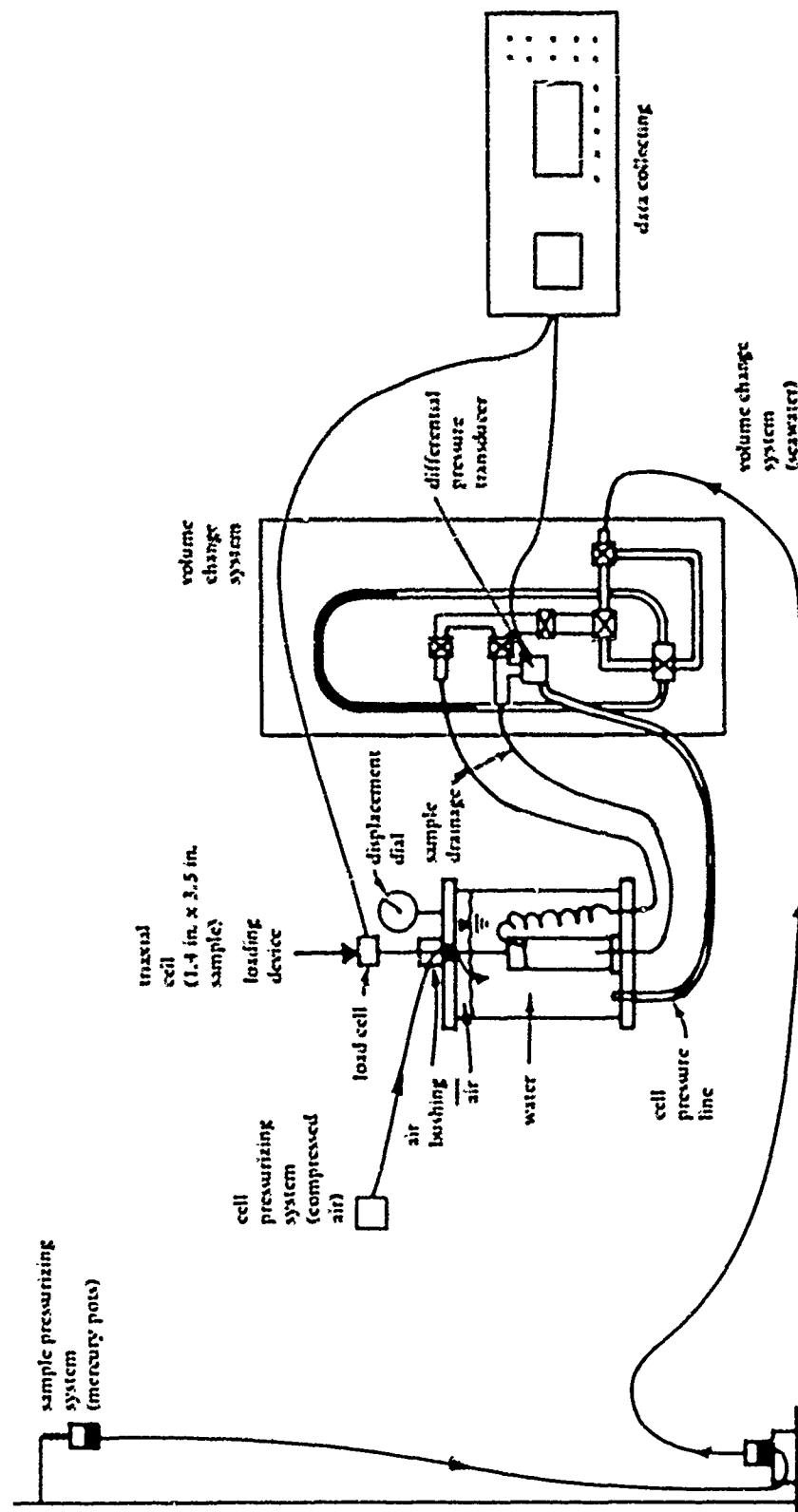


Figure 6-8. Major features of triaxial test setup.

A few specific details having to do with triaxial testing of marine sediments require discussion. First, since marine sediments have seawater as a pore fluid, the pressure lines leading to the sample should be filled with seawater rather than freshwater, if possible. No information exists to show that freshwater in the pressure lines would change behavior, but at least theoretically, changes in pore salt content could greatly alter behavior. Using saltwater in the pressure lines may introduce a corrosion problem requiring use of stainless steel fittings at critical points. A second major point is that marine sediments are considerably softer than one usually finds on land. Load and pressure transducers need to be particularly sensitive: accuracy to within 0.9 N (0.02 pound) for load and 0.15 kPa (0.02 psi) for pressure. Friction between loading rod and cell must be reduced to near zero by using such devices as air bushings.

6.2.3 Consolidation (Settlement) Parameters

The analysis of settlements has traditionally been tied in with a particular test, the one-dimensional consolidation or oedometer test. Since the principal parameters C_c , c_v , and C_s are uniquely determined by this test, the general test procedures will be described first to be followed by techniques for deriving the parameters.

In the oedometer test a disc-shaped sample of sediment is placed in a rigid circular ring with porous stones put above and below the sample (Figure 6-9). Some means for allowing drainage through the bottom stones must be allowed. Increasing loads are applied through a cover over the top porous stones. Each load increment is applied for 24 hours, and the shortening of the height of the sample is measured at frequent intervals or continuously. An initial load per unit area of 0.4 kPa (8 psf) is usually applied to soft marine sediments. The applied load is doubled each day until a relatively high pressure is reached (766 kPa, 111 psi). The load is then removed in four or five steps. Generally, an unloading loop is inserted somewhere in midtest (perhaps 200 kPa, 30 psi). The load is reduced to about one-quarter of its midtest value in three or four steps and then reloaded back.

Results are presented in two ways: (1) change of height versus \log_{10} time for each increment and (2) void ratio versus \log_{10} applied pressure for the entire test. The void ratio can be calculated for any height if the initial height and grain density are known. An example of the second type of plot is given in Figure 6-10. The two parameters C_c (compression index) and C_s (swell index) are determined directly as slopes of two portions of the curve as shown in the figure. The parameter c_v (coefficient of consolidation) is obtained from the change in height-log time curve through a more elaborate procedure (described in Lambe, 1951).

The parameters C_c and C_s are used to calculate amounts of settlement. The parameter that applies depends on whether the sediment is to be loaded beyond the maximum past pressure, $\bar{\sigma}_m$. This pressure is obtained from a graphical construction on a plot like Figure 6-10 using a procedure in Lambe (1951): (1) if field loading is to a level less than $\bar{\sigma}_m$, then C_s is used; (2) if all loading is beyond $\bar{\sigma}_m$, C_c is used; and (3) if the loading passes $\bar{\sigma}_m$, then it should be broken into two phases, and both parameters are used.

Detailed procedures for performing an oedometer test are given by Lambe (1951). The only major difference in procedure needed to account for marine sediments is the need for applying very low loads, which can be achieved by placing small weights on the loading cap. In addition, however, the sample should be submerged in seawater rather than freshwater.

6.2.4 Water Content

Water content is defined as the weight of pore seawater divided by the weight of solid sediment particles. In practice, the weight of seawater is determined as the weight of freshwater lost through drying at 105°C for 24 hours plus a salt correction of 0.035 times the weight of freshwater loss. The weight of material left behind during drying must have the same salt correction subtracted from it to obtain the weight of solid sediment particles.

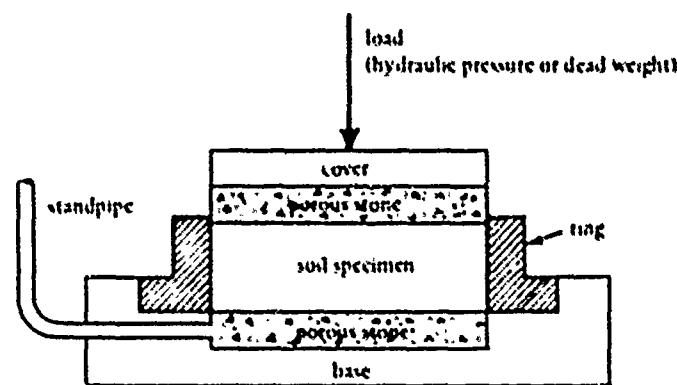


Figure 6-9. Schematic of consolidation test apparatus (after Lambe, 1951).

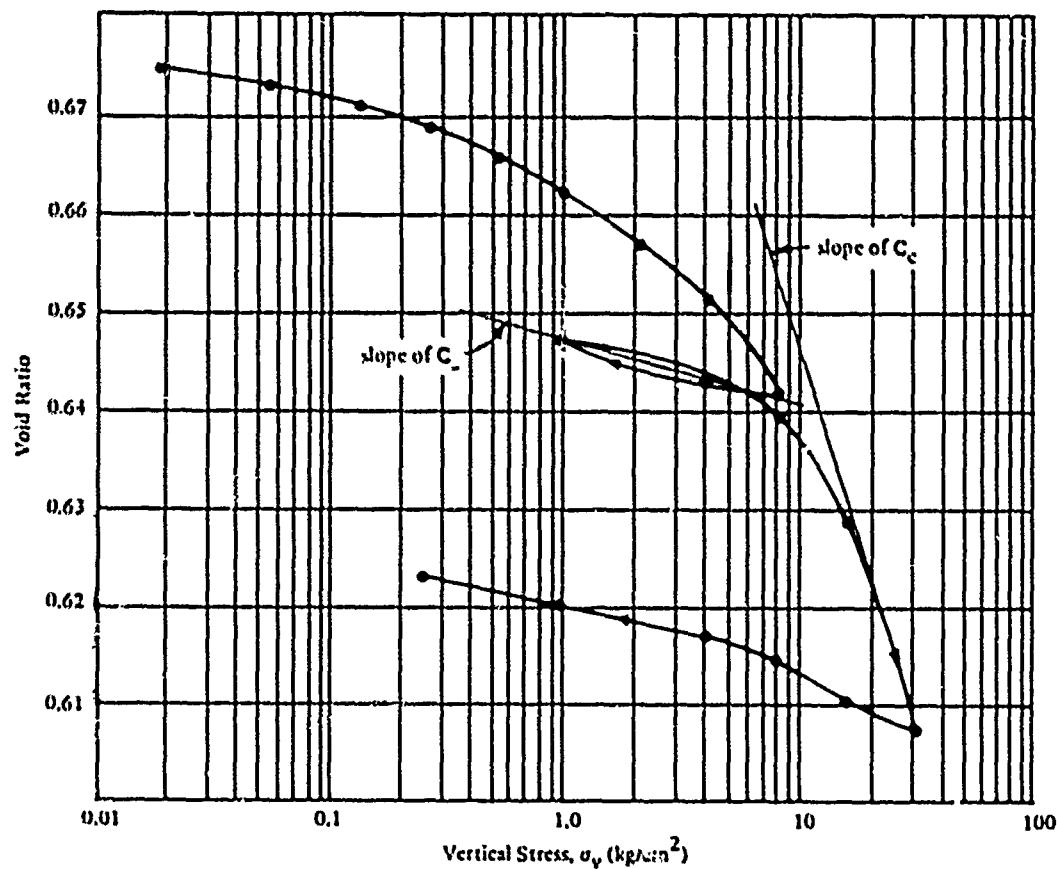


Figure 6-10. Results of oedometer test plotted as void ratio versus stress on logarithmic scale (after Lambe and Whitman, 1969).

Water content determinations should be made on samples of about 40 grams (0.1 pound). The samples are usually placed in small, previously weighed, metal tins. The sample and tin are then weighed before and after drying. Salt corrections are made, and the water content is calculated. Grain density determinations can be made on the remaining solid material not used in the water content determination.

6.2.5 Grain Density

Two common techniques are used to measure grain density (or specific gravity, as it is commonly called). In the first, the amount of sample weight lost is measured by submerging the sample in water (see Lambe, 1951 for details). The procedure described by Lambe automatically accounts for the effects salt content has on the volume determination but not for its effects on the weight determination. The weight in the numerator of Lambe's equation should have $0.035 wW_s$ subtracted from it (w is the natural water content and W_s , the weight of solids).

The second technique involves an air comparison pycnometer such as Model 930 manufactured by Beckman Instruments Inc. This device measures the volume of a sample of sediment plus any dried salts left behind. The weight of the sample should be corrected by subtracting $0.035 wW_s$ from it. The volume should be corrected by subtracting $0.035 wW_s/G_{NA}$ from it (G_{NA} is the density of sodium chloride, which is equal to 2.1 times the density of water in an approximate system of units). Detailed procedures for performing the test are given in the operating instructions for the piece of equipment chosen.

6.2.6 Index Properties

6.2.6.1 Color. Color determinations are made through comparison with Munsell soil color charts (Munsell Color Company, 1971).

6.2.6.2 Atterberg Limits. Procedures for performing Atterberg limits tests are given in Lambe (1951). Generally, both liquid limit and plastic limit would be measured and used to calculate the plasticity index for use in correlations such as that given by Figure 7-1.

Procedures have not been developed for making salt corrections to Atterberg limits. The impact of adding distilled water or drying to change water contents in the performance of limit tests is probably slight. Atterberg limit tests are generally difficult with calcareous and siliceous oozes because of their lack of plasticity.

6.2.6.3 Grain Size. Civil engineers typically determine grain size distributions through the sieve-hydrometer method. This involves washing a sample through a no. 200 sieve*, drying and sorting the material retained through a nest of sieves, and measuring the settling speed of the material that passes. The latter is done by measuring the density of a slurry as a function of time with a hydrometer. This procedure is well-described by Lambe (1951).

With most fine-grained marine sediments, it is adequate to perform the hydrometer test first using all material and then to wash the sediment-water mixture through a no. 325 sieve. The material is dried, and then a simple sieve analysis is run. The dry weight of the initial sediment is determined by making a water content determination and dividing the total wet weight of sediment to be tested by $1 + w$. Because salts are added to the graduated cylinder water, a small correction should be made. The weight of salts is calculated as $0.035 W_s / w$. A corrected water density is calculated by adding the salt weight to the weight of water and dividing by the water volume. This is used as γ_w in Lambe's equations. Lambe's parameter, r_w , should be corrected by multiplying readings in distilled water by $(1 + \gamma_w / \gamma_{fw})$ where γ_{fw} is the density of distilled water at 4°C.

*0.074-mm opening.

A few other problems arise with seafloor soils: biogenous sediments (calcareous and siliceous oozes) contain hollow or porous particles that will not obey Stoke's law, as assumed in Lambe's equations. No practical way of overcoming this problem has been found. Hydrometer test results must be interpreted as a rough index of the true grain size distribution. Another problem is that of sediments with very high interparticle adhesion forces (often associated with very high water contents). These materials are difficult to deflocculate and may require being mixed into a slurry with distilled water and repeatedly centrifuged.

6.2.6.4 Carbonate and Organic Carbon Content. Organic and carbonate carbon content may be determined with a Leco induction furnace using procedures described in the instruction manual. The weight of salts (as calculated in Section 6.2.6.3) should be subtracted from the total uncorrected dry sample weight.

7. DISTURBANCE CORRECTION

All sediment core samples are disturbed; that is, their laboratory strength properties differ from those had the samples been left in place. The difference may be slight (for many plastic, clayey sediments) to almost total (for certain coarse, biogenous oozes). Two procedures have been developed to allow the engineer to estimate in-place strength given the results of tests on partially disturbed core samples. The first (residual pore water pressure correction discussed in Section 7.1) applies to pelagic and terrigenous clays and most silts. The second (triaxial test strength profile fabrication in Section 7.2) applies particularly to sensitive silts and oozes (materials that retain no residual pore water pressure) but could be used with clays and silts as well. The second procedure involves much more time and effort.

7.1 STRENGTH CORRECTION THROUGH RESIDUAL PORE WATER PRESSURE MEASUREMENT

The first method of strength correction requires the performance of only two tests: (1) a vane shear strength (S_v) measurement and (2) a residual pore water pressure (u_r) measurement. Next, it is necessary to calculate a parameter, u_{ps} , or the reference pore water pressure.

$$u_{ps} = -\bar{\sigma}_v [K_o + A_u(1 - K_o)] \quad (7-1)$$

where $\bar{\sigma}_v$ = effective overburden pressure (Section 6.1.3)

K_o = coefficient of lateral earth pressure

A_u = reference pore water pressure parameter

The parameter A_u can be obtained from Table 7-1; the parameter K_o can be taken as 0.5 for most soft, normally consolidated sediments. If the material appears unusually stiff for its embedment depth it is necessary to estimate the overconsolidation ratio (OCR). The OCR is the ratio of the maximum overburden pressure the sediment has ever experienced to the present overburden pressure, $\bar{\sigma}_v$. This can be calculated from a consolidation test (Section 6.2.3) or estimated from the geologic history of the region. That is, if the age of the sediment is known and an approximate estimate of average sedimentation rate can be made, it is possible to calculate the amount of material that must have been removed in the past to yield the present overburden. With the OCR and the plasticity index (Section 6.2.6.2), K_o can be obtained from Figure 7-1.

The ratio u_r/u_{ps} is formed, and Figure 7-2 is entered to obtain S_u/S_v . This is the strength correction factor that is multiplied by the measured vane shear strength, S_v , to obtain the estimated in-place undrained shear strength, S_u . Strength correction factors higher than about 2.5 are questionable. If such high values are found, one should use the triaxial test profile fabrication method (Section 6.2). Figure 7-2 was derived from data on terrigenous silty clays. Although it has not been shown, it is reasonable to assume that it is also applicable to pelagic clays.

Table 7-1. Reference Pore Water Pressure Parameter, A_u ^a

Soil Type	A_u
Normally consolidated	
Clayey silt	-0.1
Lean clay	0.15
Plastic clay	0.25
Heavily overconsolidated	
Plastic clay	0.3

^aReprinted by permission of the American Society for Testing and Materials, Copyright (Ladd and Lumbe, 1963).

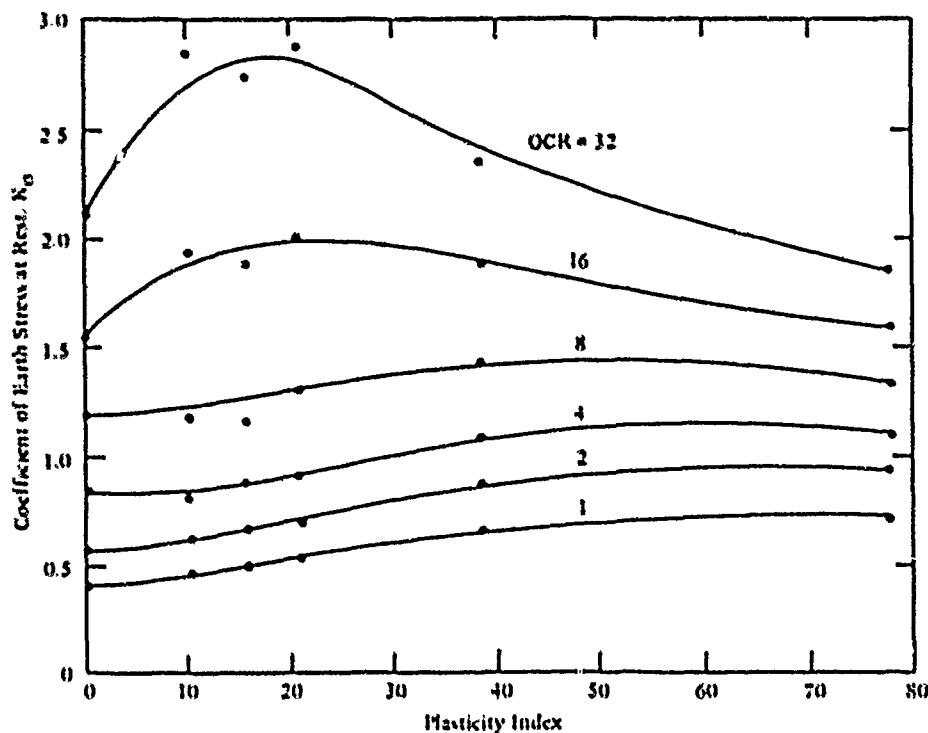


Figure 7-1. Term K_o as a function of OCR and plasticity index (from Brooker and Ireland, 1965).

7.2 TRIAXIAL TEST STRENGTH PROFILE FABRICATION

In the triaxial test samples are subjected to the overburden pressure conditions of sediments from greater subbottom depths. The consolidation process removes many of the effects of disturbance since, in a sense, a new, simulated deep sediment is created. As long as consolidation is to about three or four times the in-place overburden pressure of the sample tested, it can be assumed that most disturbance effects have been removed.

The method of strength profile fabrication through triaxial testing requires the application of the following equation:

$$\frac{S_u}{\bar{\sigma}_v} = \frac{[K_o + \bar{A}_f(1 - K_o)] \sin \bar{\phi} + (c/\bar{\sigma}_v) \cos \bar{\phi}}{1 + (2 \bar{A}_f - 1) \sin \bar{\phi}} \quad (7-2)$$

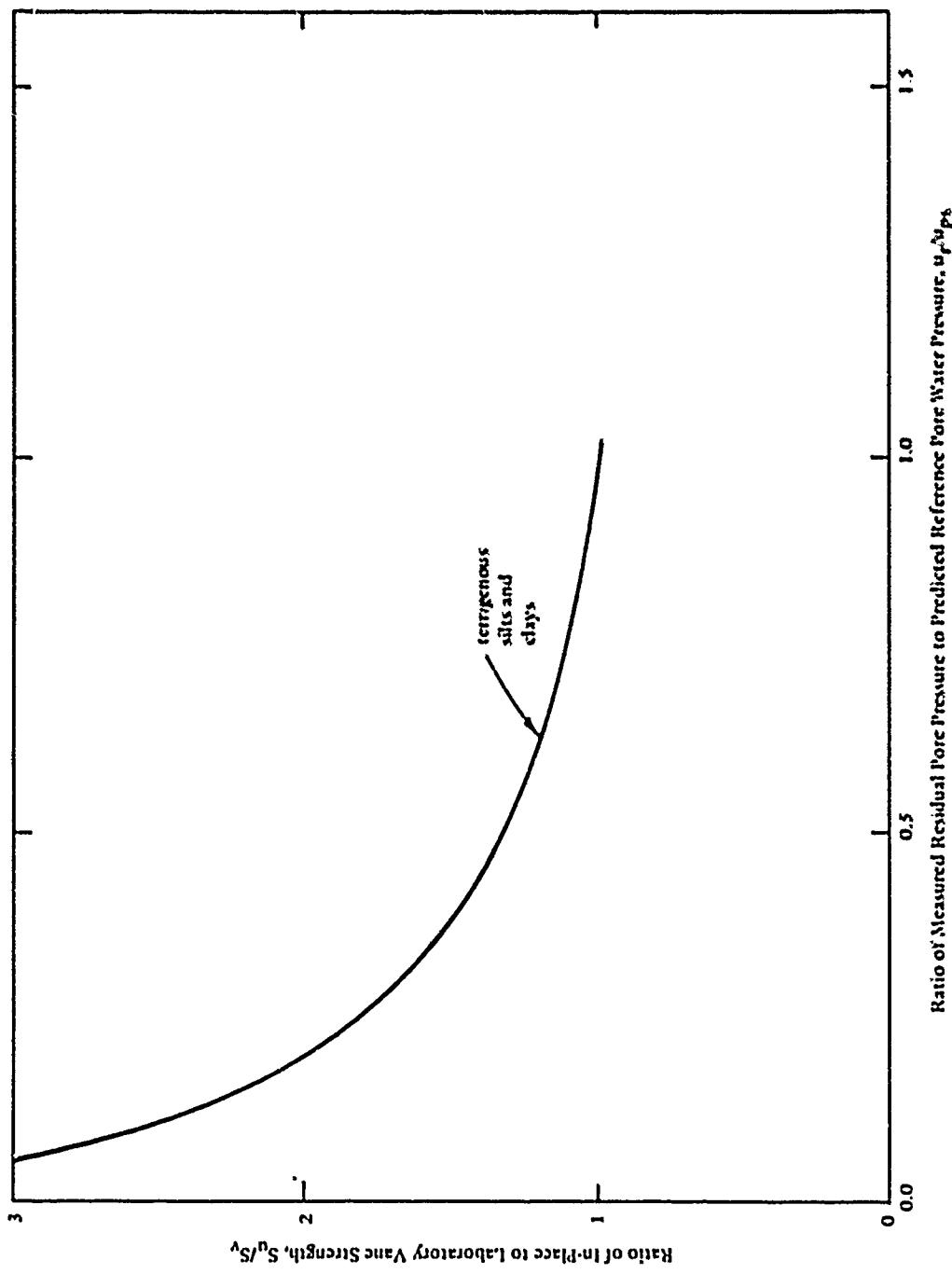


Figure 7-2. Normalized strength versus normalized residual pore pressure for terrigenous silty clays.

where $\bar{\sigma}_v$ = overburden pressure at depth where strength, S_u , is to be predicted (Section 6.1.3)
 K_o = coefficient of lateral earth pressure (Section 7.1)
 c, ϕ = strength envelope parameters from triaxial tests
(at least three tests on three samples required)
(Section 6.2.2.1)
 A_f = pore pressure parameter (see the following paragraph)

All of these parameters except A_f have been defined previously.
The parameter, A_f , is obtained as follows (see Figure 7-3):

(1) On the stress path plot for the triaxial tests performed, a line is constructed through the origin with a slope

$$\frac{q}{p} = \frac{1 - K_o}{1 + K_o}$$

(2) At the point where this line crosses the individual stress paths, the appropriate values of \bar{p} and q are determined and identified as \bar{p}_o and q_o .

(3) The values of \bar{p} and q at failure are obtained and identified as \bar{p}_f and q_f .

(4) The parameter A_f is calculated as:

$$A_f = \frac{\Delta q - \Delta \bar{p}}{2\Delta q} \quad (7-3)$$

$$\Delta q = q_f - q_o$$

$$\Delta \bar{p} = \bar{p}_f - \bar{p}_o$$

(5) A_f usually varies with overburden pressure. The correct value of $\bar{\sigma}_v$ for each value of A_f is $\bar{p}_o + q_o$. A_f is plotted versus the appropriate values of $\bar{\sigma}_v$. Values of A_f are interpolated for other $\bar{\sigma}_v$'s.

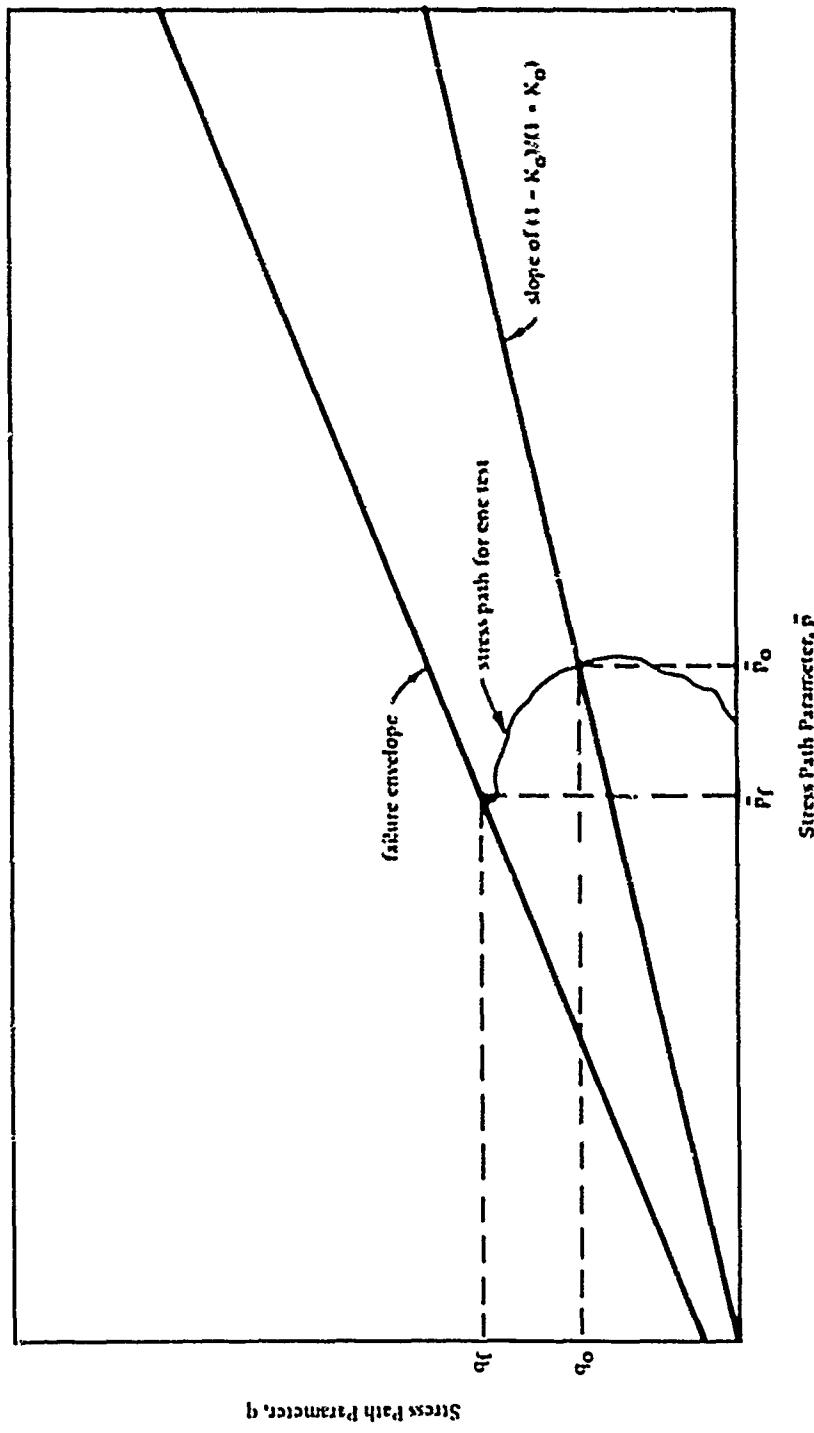


Figure 7-3. Definition of terms for calculation of A_f .

Equation 7-2 can be used readily to construct plots of predicted S_u versus $\bar{\sigma}_v$ (which can be quickly related to subbottom depth). It is important in making these fabrications to use results of triaxial test on materials basically the same as those whose strengths are being predicted. To check whether this condition is met, one should compare index properties of the material being triaxial tested (which may be from a box core or shallow gravity core) with those of the material whose strength is being predicted (which may be from a long-piston core). Color, grain size, Atterberg limits, and carbonate content should be approximately equal.

8. ACKNOWLEDGMENT

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Appendix A

BACKGROUND RESEARCH

This handbook represents the conclusion of an 8-year program at CEL in the investigation of methods for determining the engineering properties of marine sediments. The main text includes guidelines and rules for taking cores, performing laboratory tests, and estimating properties. This appendix summarizes the research and development program followed to produce the guidelines and rules; also to be noted are references to publications upon which the recommendations of the main text are based.

This work began in July 1970 with the basic philosophy that coring followed by laboratory testing presents a viable method for obtaining good estimates of the in-place engineering behavior of marine sediments. At the time, most marine geotechnologists were favoring either expensive in-place tests performed by bottom-resting platforms or incremental coring from large-bottom platforms. These people believed that typical oceanographic corers introduced such high levels of disturbance that engineering properties measured were practically meaningless. In disagreement with this common philosophy were those who showed that strengths obtained from conventional core samples did not vary greatly from strengths obtained in place or from strengths of cores taken by fixed platform. Also, research conducted several years previously at Massachusetts Institute of Technology (Ladd and Lambe, 1963) could be applied to correct for the disturbance that did exist. By use of conventional or slightly modified corers and correcting for sample disturbance, considerably more economical operations, as well as sampling to greater subbottom depths and provision for obtaining long-term (drained) properties through triaxial testing, would result.

In the first phase of the work, a methodology was developed for disturbance correction through in-place testing, coring, and laboratory testing of the cores (some of which were artificially disturbed). The CEL Deep Ocean Test-in-Place and Observation System (DOTIPOS) platform (Demars and Taylor, 1971) was deployed in 1971 at three Santa Barbara Channel test sites and performed in-place vane tests immediately adjacent to (within 1 meter of) locations where truly fixed piston cores had been obtained. Several gravity cores were taken at the same sites. Some of the cores were artificially disturbed (through vibration, long-term storage, etc.), and all were tested for laboratory vane shear strength and residual pore water pressure. A curve that related laboratory with in-place vane strengths through residual pore pressure

measurements was developed and assumed to apply to terrigenous silts and clays (Lee, 1973a). A triaxial testing facility was set up, and procedures for triaxial testing of weak, near-surface marine sediments were developed. An extensive program (50 tests) of triaxial testing of the Santa Barbara Channel DOTIPOS cores was conducted. This work provided the basis for the procedures for fabricating strength profiles using triaxial tests.

In the summer of 1971, CEL participated in Leg 19 of the Deep Sea Drilling Project in the Bering Sea and far northern Pacific Ocean. Typical properties of siliceous oozes were obtained, and it was shown that the drilled samples taken by the D/V GLOMAR CHALLENGER are highly disturbed (Lee, 1973b, 1973c). Numerous consolidation tests were performed and indicated some peculiar traits of biogenous oozes.

In 1972 two, high quality, box core samples of pelagic clay were obtained and subjected to triaxial tests. The strength profile fabrication procedure was finalized, and a profile to a subbottom depth of 30 meters (100 feet) was estimated (Lee, 1973d, 1974).

In 1973 CEL participated in Leg 27 of the Deep Sea Drilling Project in the eastern Indian Ocean (Rocker, 1974) and obtained typical properties of fine-grained calcareous (nanno) oozes. Three conventional 10-meter (30-foot) long-piston cores were obtained at a CEL Santa Barbara Channel site. A technique that used a large drag spool to prevent piston rebound was developed. The shear strengths of these samples were found to vary little from those of the fixed-piston DOTIPOS cores obtained in 1971.

In late 1973 and 1974, five cruises were conducted in the California borderlands area and the western Atlantic Ocean. The objective was to expand the disturbance correction procedure to deep ocean oozes and clays. In-place vane strengths were measured with the Office of Naval Research (ONR) vane shear device (Richards et al., 1972), and cores were taken with a conventional piston corer. It was found that the residual pore pressure method of disturbance correction was not applicable to some calcareous oozes but that the triaxial test profile fabrication method could be used (Lee, 1976).

In 1975 and 1976, several corers and coring procedures were evaluated, including the SACLANT sphincter corer, the SACLANT fixed piston, and the Niskin water mass. Procedures for deploying large corers from Navy AGOR vessels were developed. Typical properties of equatorial siliceous and calcareous oozes were determined as a result of a cruise to the eastern equatorial Pacific Ocean in the summer of 1976 (Lee, 1978).

In 1977 long-piston cores of pelagic clay were obtained at a site where only box core samples were available previously. The box cores had been used to fabricate a strength profile through triaxial tests (Lee, 1976), and the strengths of the piston cores were found to follow the predicted values extremely well (Figure A-1). A comparison of laboratory strengths with Doppler Penetrometer tests was used to derive residual pore pressure correction data for pelagic clay.

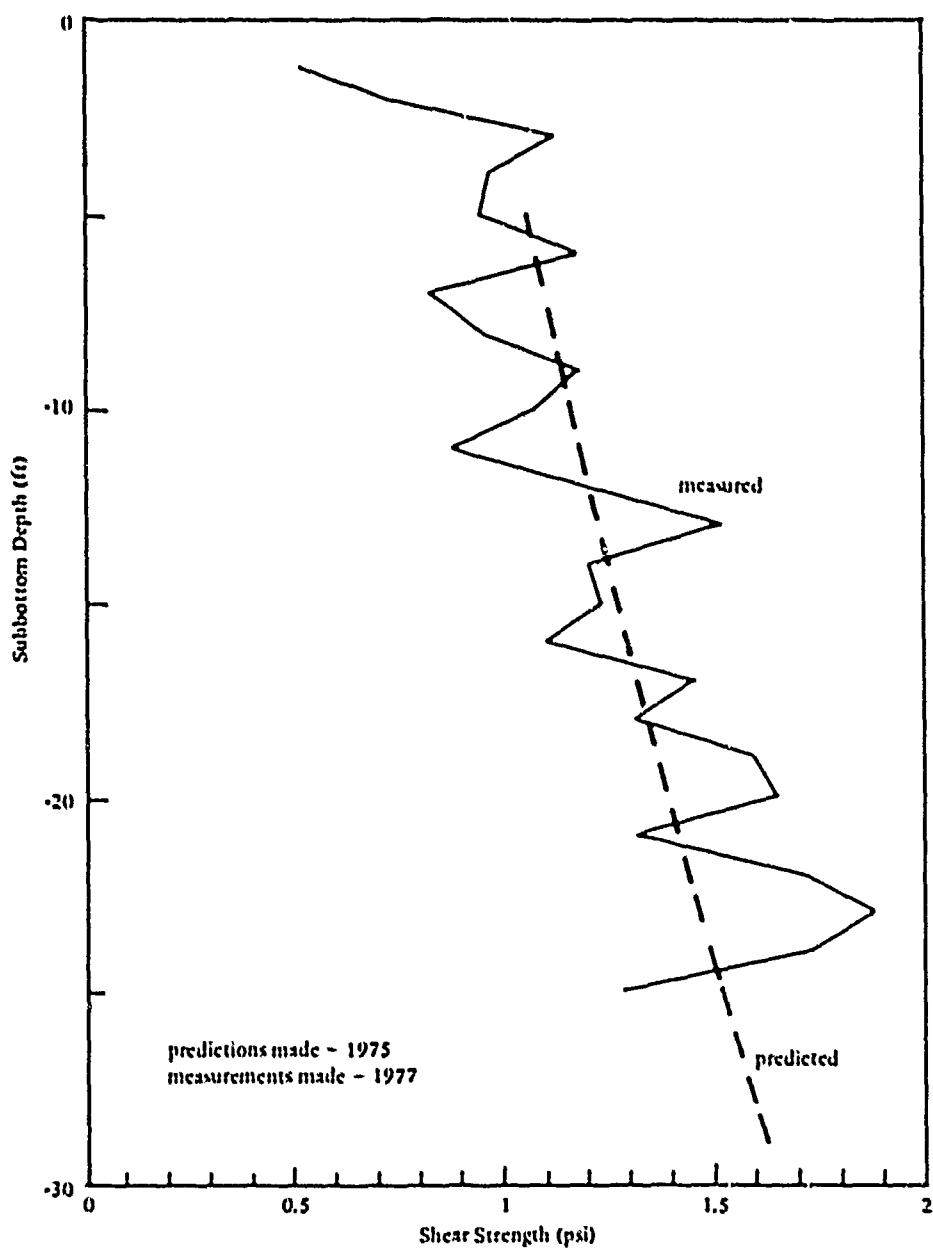


Figure A-1. Comparison of measured and predicted shear strengths of pelagic clay (predictions developed through triaxial test fabrication).

Appendix B
ORGANIZATIONS CITED IN TEXT

Alpine Geophysical Associates, Inc.
Ocean Services Division
70 Oak Street
Norwood, NJ 07648
(201) 768-8000

Beckman Instruments, Inc.
2500 Harbor Boulevard
Fullerton, CA 92634
(714) 871-4848

Benthos, Inc.
Edgerton Drive
N. Falmouth, MA 02556
(617) 563-5917

Hydro Products, Inc.
11777 Sorrento Valley Road
San Diego, CA 92121
(714) 453-2345

InterOcean Systems, Inc.
3540 Aero Court
San Diego, CA 92123
(714) 565-8400

Intersea Research Corporation
P.O. Box 2389
La Jolla, CA 92038
(714) 453-5200

Kahl Scientific Instrument Corp.
737 W. Main Street
El Cajon, CA 92022
(714) 444-2158

Lamont-Doherty Geological Observatory
of Columbia University
Palisades, NY 10964
(914) 359-2900

Naval Facilities Engineering Command
Chesapeake Division
Bldg. 57
Washington Navy Yard
Washington, DC 20374
Autovon 288-3881

Naval Oceanographic Office
Code 3100
National Space Technology Laboratories
NSTL Station, MS 39522
Autovon 485-4635

Naval Research Laboratory
455 Overlook Avenue, S.W.
Washington, DC 20375
(202) 767-3403

NOAA

- (1) 6001 Executive Boulevard
Rockville, MD 20852
(301) 443-8101
- (2) Chief of Operations Division
National Ocean Survey, NOAA
1801 Fairview Avenue, East
Seattle, WA 98102
(206) 442-7657
- (3) Chief of Operations Division
National Ocean Survey, NOAA
1439 W. York Street
Norfolk, VA 23510
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LIST OF SYMBOLS

A	Metallic cross-sectional area of wire rope	D	Depth of penetration of trip corer or trip weight	k	Distance of gravity
A_c	Corrected area of a triaxial sample	D_c	Inside diameter of cutter	L	Maximum
A_f	Pore pressure parameter	D_s	Inside diameter of barrel or liner	L_g	Length of
A_n	Frontal area of penetrometer nose	D_t	Outside diameter of barrel	l	Length of
A_o	Original cross-sectional area of a triaxial sample	D_w	Outside diameter of cutter	N_c	Bearing
A_s	Side area of a penetrating object	d	Vane diameter	n	Porosity
A_u	Reference pore water pressure	E	Modulus of elasticity of the wire rope	$-p$	Stress p
a	Intercept	e	Void ratio	$-p_c$	Different pressure
C	Safe length-to-diameter ratio	F_{AD}	Force on side of penetrometer	$-p_f$	Value of p at fail
C_a	Area ratio	F_B	Breakout force	$-p_o$	Initial v parameter
C_c	Compression index for normally consolidated soils	F_{BE}	Force on nose of penetrometer	q	Stress p
C_D	Drag coefficient	F_f	Free-fall height	q_f	Value of q at fail
C_i	Inside clearance	F_H	Inertial drag	q_o	Initial v parameter
C_l	Length of corer	F_T	Total force	R	Reflection
C_o	Outside clearance	G	Grain density	r	Height tr release c
C_s	Recompression or swell index for overconsolidated soils	G_{NA}	Density of sodium chloride	r_w	Parameter size equ
c	Sound speed of sediment	H	Vane height	S	Amount of
c_o	Sound speed of water	i	Distance from pivot to corer bail	S_e	Strain rat
c_v	Coefficient of consolidation	j	Distance from pivot to trigger weight	S_t	Sediment
$-c$	Drained cohesion intercept	K_o	Coefficient of lateral earth pressure		

ace from pivot to center
vity of trip arm

Sampling length

of line out

of trip cable

g capacity factor

ity

path parameter

ential or consolidation
ure

of stress path parameter
failure

l value of stress path
ter p

path parameter

of stress path parameter
failure

l value of stress path
ter q

tion coefficient

trip arm must move to
corer

ter in Lambe's grain
quation

of elastic stretch

rate effect

st sensitivity

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